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GEOTEXTILE REINFORCED EMBANKMENTS ON SOFT FOUNDATIONS

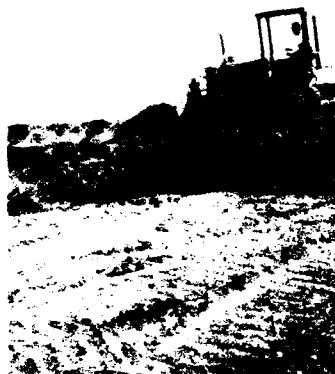
by

Jack Fowler

Geotechnical Laboratory

DEPARTMENT OF THE ARMY

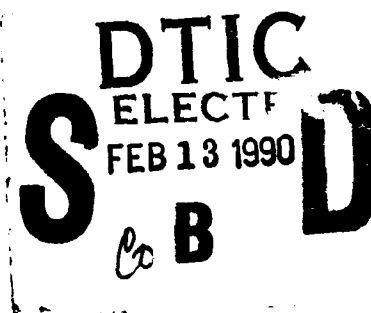
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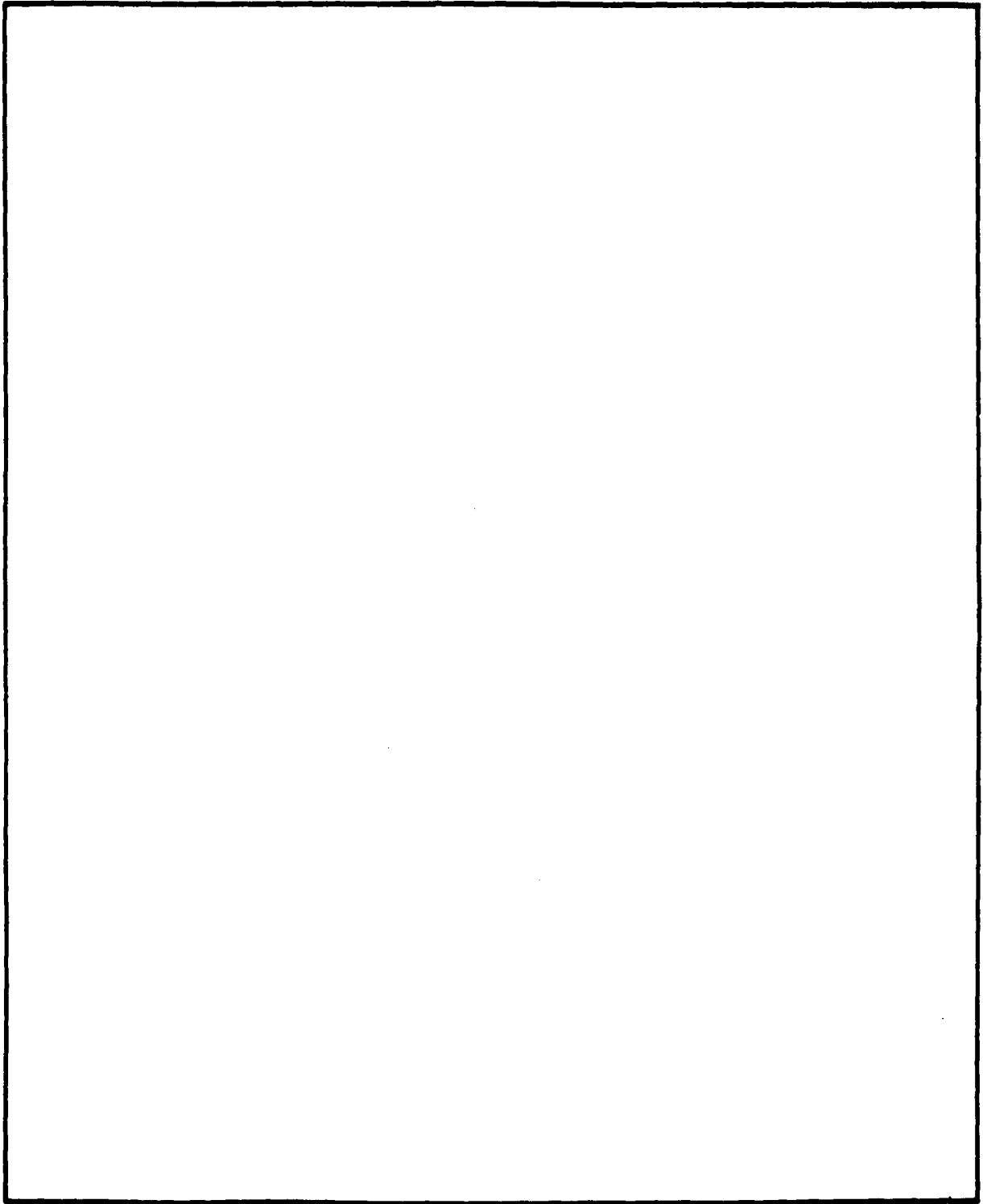
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PREFACE

This publication describes the design and construction techniques for geotextile reinforced embankments over soft foundations at a number of locations throughout the United States.

The report was prepared by the Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for the International Geotextile Seminar 1989, Osaka, Japan, 27-29 November 1989 for the Chapter of International Geotextile Society Organizing Committee for International Geotextile Seminars.

The report was written by Dr. J. Fowler, under the general supervision of Mr. G. B. Mitchell, Chief, Engineering Group, Soil Mechanics Branch (SMB), Dr. D. C. Banks, Chief, Soil and Rock Mechanics Division (S&RMD), and Dr. W. F. Marcuson III, Chief, GL. Mr. W. L. Hanks provided technical assistance in preparation of the report.

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CONTENTS

	<u>Page</u>
PREFACE	1
CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT	4
PART I: INTRODUCTION	5
Purpose	5
Objectives	5
Scope	6
PART II: CONVENTIONAL EMBANKMENT CONSTRUCTION ON SOFT FOUNDATIONS	7
Construction Alternatives	7
Discussion of Construction Alternatives	8
Pre-load and Staged Construction	8
Consolidation by Surcharge	8
Use of Lightweight Fill Material	8
Floating Section with Berms	10
Displacement Section	10
Excavation and Replacement	11
Fabric-Reinforced Embankments on Soft Foundations	11
PART III: CASE HISTORIES	14
Fabric Reinforcement Embankment on Muskeg, Petersburg, Alaska	14
Dredged Material Containment Dike, Brunswick, GA	16
Fabric Reinforced Embankment, Swan Lake, Mississippi	18
Fabric Reinforced Embankment Controlled Failure Holland	22
Fabric Reinforced Embankment, Pinto Pass, Mobile, Alabama	24
Fabric Reinforced Embankment, Craney Island, Norfolk, District	26
Seagirt Project, Baltimore, Maryland	27
Wilmington, Delaware Strip Drain and Fabric	28
Fabric Reinforced Containment Dike, New Bedford Superfund Site	29
Mohicanville	29
Other Examples	30

	<u>Page</u>
PART IV: POTENTIAL EMBANKMENT FAILURE MODES	32
Horizontal Sliding, Splitting, and Spreading	32
Rotational Slope and/or Foundation Failure	33
Excessive Vertical Foundation Displacement	33
PART V: OTHER CONSIDERATIONS IN FABRIC-REINFORCED DIKE CONSTRUCTION	36
Existing Fabric-Reinforced Embankment Design Concepts and Geotextile Function	36
Existing Design Concepts	36
Creep	38
Fabric Anchorage Systems	38
Fabric Properties for Reinforcement Applications	40
Formation Soil Crust or Root Mat	40
Recommended Criteria	40
Overall Bearing Capacity	42
Slope Stability Analysis	43
Sliding Wedge Analysis	46
Embankment Spreading Failure Analysis	48
Potential Embankment Rotational Displacement	49
Longitudinal Fabric Strength Requirements	50
Embankment Deformations	50
Factor of Safety	52
Example of Fabric-Reinforced Embankment Design	53
The Assumption	53
The Specifications Required	53
The Solution	53
Bearing Capacity Consideration	55
Fabric-Reinforced Embankment Construction	62
Equipment Selection	62
Site Preparation	67
Fabric Placement Procedures	68
Fill Placement/Spreading/Compaction Procedures	69
Construction Sequence for Fill Material Placement	69
Discussion of Construction Procedures	72
Benefit-Cost Ratio Determination	72
PART VI: CONCLUSIONS AND RECOMMENDED DESIGN AND CONSTRUCTION CONSIDERATIONS	73
Important Design Considerations and Recommendations	73
Important Construction Considerations and Recommendations	74
General Recommendations	75
REFERENCES	76

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
acres	4,046.873	square metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
feet per day	0.3048	metres per day
feet per minute	0.3048	metres per minute
inches	2.54	centimetres
pounds (force) per square foot	47.88026	pascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres
square feet per day	0.09290304	square metres per day
square inches	6.4516	square centimetres
tons (force) per square foot	95.76052	kilopascals

GEOTEXTILE REINFORCED EMBANKMENTS ON SOFT FOUNDATIONS

PART I: INTRODUCTION

1. Historically, practically every material known to man has been used to reinforce or separate embankments and roadways on/from soft foundation materials. In the past four decades there has been continued development of high performance geotextiles or synthetics products that have proven to be more economical, easier to handle, stronger and longer lasting than traditionally used construction materials. These geotextiles must resist a range of acid and basic soils and liquids including ultra violet light and creep under sustained loads for long periods of time. There have been a number of case histories in the past four decades that support and verify the technical and economical feasibility of this construction technique. This paper is the result of many of those case histories and the recommended design and construction procedure presently practiced by the US Army Corps of Engineers.

Purpose

2. This paper will provide the information necessary for the proper design and construction of geotextile reinforced embankments over soft foundations.

Objectives

3. The objectives of the paper will be to present the latest design and construction techniques and methodologies practiced by the Corps of Engineers. Hopefully, the reader should be (a) familiar with conventional soft ground construction alternatives and their limitations, (b) familiar with how a geotextile functions as an reinforcement in an embankment, (c) able to utilize the design and construction criteria as presented and (d) able to specify fabrics and construction procedures necessary to ensure satisfactory performance of fabric-reinforced embankments over soft foundations.

Scope

4. The scope of this report will include design and construction techniques for geotextile reinforced embankments constructed over soft foundations.

PART II: CONVENTIONAL EMBANKMENT CONSTRUCTION ON
SOFT FOUNDATIONS

5. Conventional dikes construction on extremely soft foundations in the past has been well defined by many years of experience. The general procedure for dike construction is as follows:

- a. The embankment alignment is cleared of vegetation and debris, and the top soil is removed.
- b. Select dike fill material is placed in thin lifts of 6 to 8 in. and compacted to a design density and optimum moisture contents.
- c. After the dike is constructed to design height, it is shaped, covered with stockpiled top soil, and seeded.

Construction Alternatives

6. The construction conditions assume that the foundation will provide the necessary support for construction equipment mobility during fill placement and compaction, and that the foundation bearing capacity is sufficient to support the dike to design height. If these conditions are not met, the embankment may fail during or after construction by sliding wedge or circular arc-type failure (shallow and/or deep seated) or by excessive subsidence caused by soil consolidation, creep, or foundation displacement from a simple bearing capacity failure. Alternatives for conventional embankment design and construction on soft foundation are as follows:

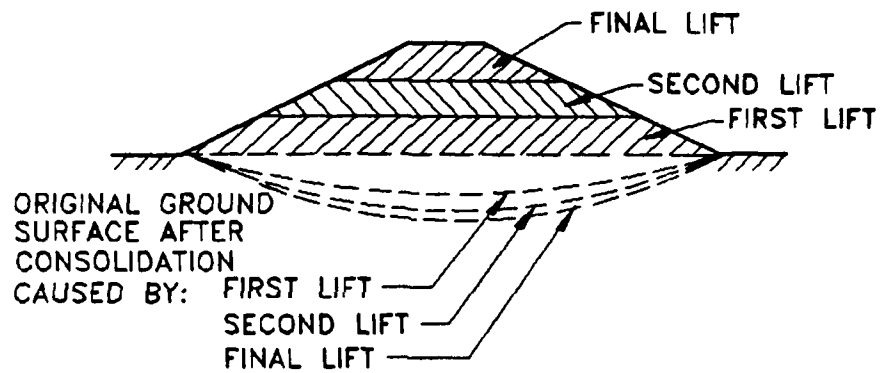
- a. Foundation pre-loading and/or stage construction and thin lifts over a period of years.
- b. Use of lightweight fill material such as shell or slag.
- c. Construction of floating sections with wide berms.
- d. Excavation and replacement of undesirable foundation material.
- e. A displacement section that displaces undesirable material.
- f. Fabric-reinforced dikes.
- g. Steel wire, steel straps, synthetic strips (fiberglass, polymer, carbon fiber, etc.) could also be used.

Discussion of Construction Alternatives

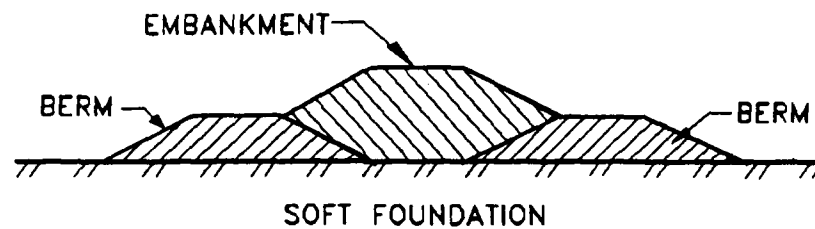
7. Pre-load and Staged Construction. Foundation pre-loading/stage construction with and without strip drains. Pre-loading, or stage embankment construction, is a viable alternative to consolidate the soft subgrade material before the structure has been constructed to its design height. Construction is generally conducted by end dumping and spreading fill material along the center line of the embankment alignment to the maximum safe heights which may be obtained without causing foundation failure. The embankment is then monitored for a period of time until the excess pore water pressure has dissipated and the undrained shear strength of the soil has increased. After the foundation has consolidated, the embankment is raised to a new maximum safe height above the base. The embankment is sequentially raised in this manner until the design height is reached. The foundation pre-loading/stage construction technique is illustrated in Figure 1a. This technique can be used only if there is sufficient time to allow foundation consolidation without failure, which might result from constructing the embankment too high or by allowing additional construction before adequate foundation consolidation has taken place.

8. Consolidation by Surcharge. Consolidation by surcharge may also be achieved in combination with vertical sand drains or strip drains, which would accelerate the process. The use of strip drains has practically eliminated the use of vertical sand drains. Strip drains with geotextiles have become quite popular in the last few years. The geotextile is normally placed on the soft foundation materials, a 2 to 3 ft cover of sand is then placed to support the strip driving machine, and finally the drains are driven through the sand cover and geotextile into the soft foundation material. Subsequently a surcharge load is added to the 2 to 3 ft cover material and the foundation materials are allowed to consolidate. Soft foundation material that lay over previous soils or that contain stratified layers of soft materials may also be consolidated with pressure relief wells, vertical sand drains, or strip drains placed along the toe of a fill.

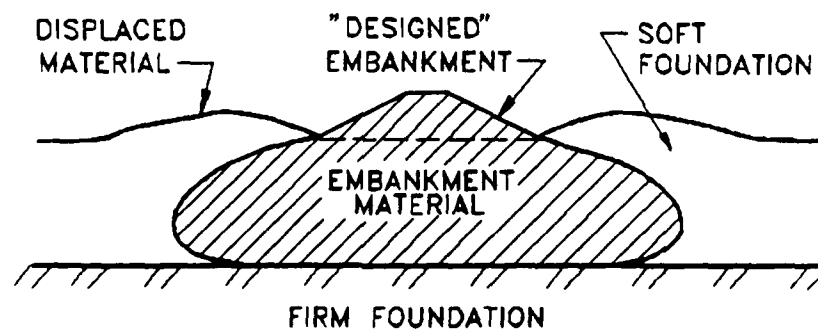
9. Use of Lightweight Fill Material. Lightweight embankment fill material such as wood chips, wood debris, lightweight slag, reef shell, oyster shell, or clam shell may be used to reduce the foundation stress from the



PRELOADING/STAGED CONSTRUCTION



FLOATING SECTION WITH BERMS



DISPLACED SECTION

Figure 1. Conventional embankment construction alternatives of pre-loading/staged construction, a floating section with berms, and a displacement section.

embankment weight. Construction techniques are generally the same as those used in conventional construction, with the exception of using lightweight material. Many problems are still associated with this type of construction:

- a. Fill material mechanical properties are quite often not known and may cause dike instability.
- b. Biological degradation of organic fill material may present unknown problems.
- c. Placement and compaction of fill material with specific gravity less than 1 may also present problems.
- d. Unknown economic expense and difficulty obtaining suitable lightweight fill materials.
- e. Fill compaction, placement, and spreading with conventional equipment.

10. Floating Section with Berms. In the event that a stability analysis indicates that a rotational shear failure or a sliding wedge shear failure will most likely occur, then a floating embankment section constructed with berms may be the best construction alternative. An example is shown in Figure 1b. When properly constructed, the berms will serve as counterweight or counterbalance to the internal embankment forces which would otherwise cause rotational shear failure. This alternative is called a floating section because the berms prevent a mud wave formation along each toe, and the embankment appears to be floating on the very soft foundation. The use of wide, shallow berms allows the embankment to be constructed to heights greater than normally obtained by conventional construction techniques. Some of the major disadvantages of this technique are that the foundation may not be able to support the construction equipment and may cause equipment mobility problems resulting in a displacement section. Strength loss in the foundation material caused by construction traffic remolding has resulted in strength reduction of 60 to 80 percent.

11. Displacement Section. Displacement of the soft foundation materials by the embankment weight is another common construction alternative. This technique may alleviate some of the equipment mobility problems that are associated with soft foundation construction. It is quite simple and may be used in very shallow or very deep foundation areas if enough backfill material is available. Fill material is generally hauled by scrapers or trucks, end-dumped, and spread progressively from the center line of the embankment to each side displacing downward, and shoving unsuitable material downward and

outward to each side. Figure 1c shows a typical embankment constructed by this technique. The technique has many advantages in that it requires no design, and it only requires brute force and mass of the heavy construction equipment that continuously fails the foundation. Since it depends on foundation failure, equipment mobility problems are maximized. Displacement sections generally require 3 to 5 volumes of soil below the surface to support 1 volume of material above the surface. Therefore, the cost of fill material and the placement of these materials are very expensive. During construction, a mud wave may appear in front of the displaced section. This mud may have to be removed by a dragline that excavates material and either places it to the sides of the embankment or it is hauled off the site by dump trucks. A problem associated with this method is that during construction, soft material may become entrapped within the embankment fill material and prevent equipment mobility, thus preventing the continued construction of the embankment and limiting the final embankment cross section to less than that desired.

12. Excavation and Replacement. In the event that the soft foundation materials are found to exist only in shallow depths, these may be removed and replaced with suitable backfill material, thus reducing or minimizing any embankment stability problems or foundation settlements. This technique has been successful in construction of embankments on very soft foundation. This alternative should be considered when fill material and borrow sources are limited. Figure 2 shows various excavated and replaced sections and some design concepts that have been successful in the past. However, there are several disadvantages. Excavation of high water content cohesive soil may be very expensive and often impossible to remove because of equipment mobility problems, backfill material cost may be very high, and this technique is often limited to shallow foundation deposits.

Fabric-Reinforced Embankments on Soft Foundations

13. Quite often, conventional construction techniques will not allow dikes to be constructed on very soft foundations because it may not be cost effective, operationally practical, or technically feasible. Nevertheless, fabric-reinforced dikes that were designed and constructed by the US Army

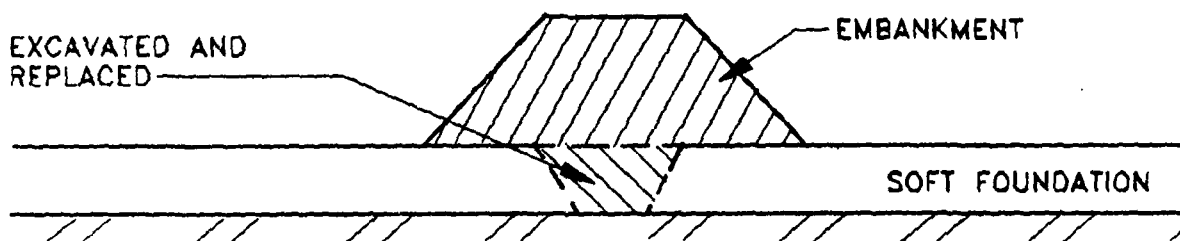
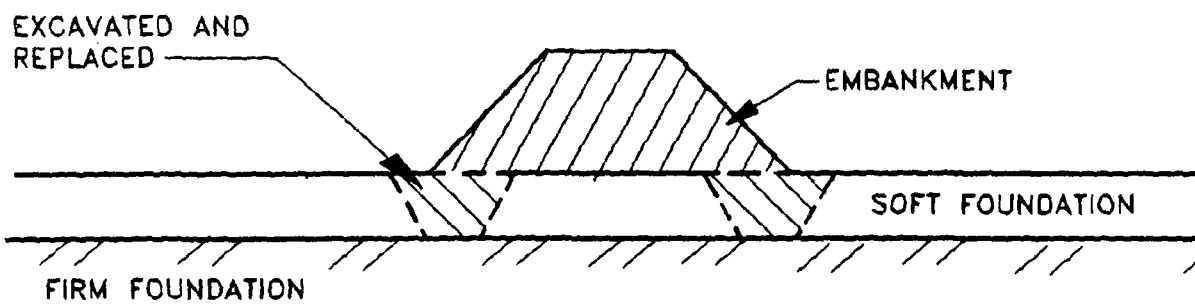
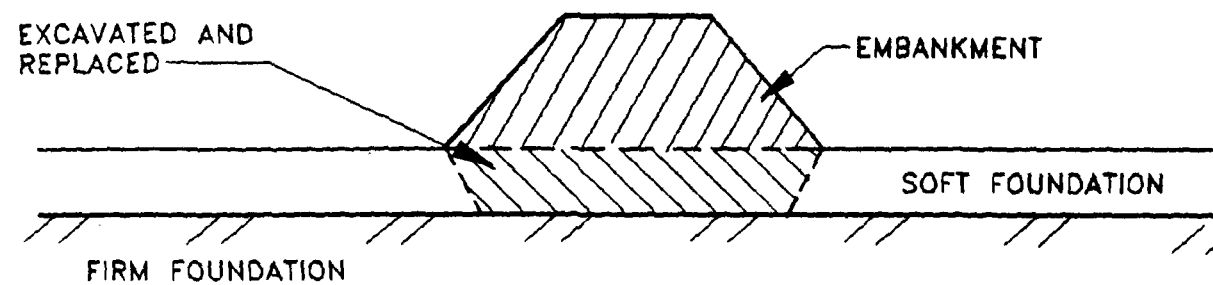


Figure 2. Typical excavated and replaced sections used for embankment construction on soft foundations of shallow depth.

Engineer Waterways Experiment Station at Pinto Pass, Mobile, Alabama; Craney Island, Virginia; Wilmington, Delaware; New Bedford, Massachusetts; and New Orleans, Louisiana have been made to float on very soft foundations without failure. Fabrics used in those dikes alleviated many soft ground foundation dike construction problems because they permit better equipment mobility, allow expedient construction, and allow construction to design elevation without failure.

14. Design parameters and analytical procedures used for design and fabric selection in construction of the Pinto Pass and Craney Island dikes have been verified (Haliburton 1980). Test sections and construction procedures and techniques necessary for the successful completion of these dikes to design heights have also been identified (Fowler 1979). Therefore, the next few paragraphs will only address the potential failure modes and requirements for design and selection of fabrics for reinforced dikes.

PART III: CASE HISTORIES

15. Case histories of fabric reinforcement embankments. There have been a number of fabric reinforcement embankments constructed to date that can be found in the literature. The case histories to be discussed in the following sections will help illustrate the subsurface conditions, geotextile types, design and construction procedures which formed the basis for the design criteria to be discussed in later sections.

Fabric Reinforcement Embankment on Muskeg, Petersburg, Alaska

16. Bell et al., 1977, documented construction and performance of a 700-ft long fabric reinforced low embankment constructed on a Muskeg or peat foundation near Petersburg, Alaska. Foundation shear strengths ranged from 50 psf to 250 psf and average water contents were approximately 960 percent. The peat ranged in depth from 8 to 11 ft with an average depth of about 10 ft. A non-woven needle punched fabric was used for reinforcement and was placed directly on the ground surface prior to fill placement. The embankment fill consisted of pit run quarry rock coarse sand and up to 4-ft diam boulders were placed directly on the fabric. Embankment height ranged from 2- to 8-ft above the fabric. Figure 3 shows a typical section of the reinforced embankment that was proposed to be constructed.

17. Settlement plates were installed in the embankment and very simple strain gages were attached to the fabric. The settlement plate measurements indicated that there were two types of fabric embankment subsidence. One relating to bearing failure and the other related to foundation compression. The strain gages were of the type that were only able to determine maximum strength. The strain gages indicated little or no strain at the end of construction but about three months after the end of construction the strains varied from 5 to 50 percent. Even though the embankment experienced excessive displacement, Bell et al., 1977, calculated a 28 percent saving in fill material as compared to conventional no fabric construction. They also concluded that the main function of the fabric was to prevent local bearing capacity

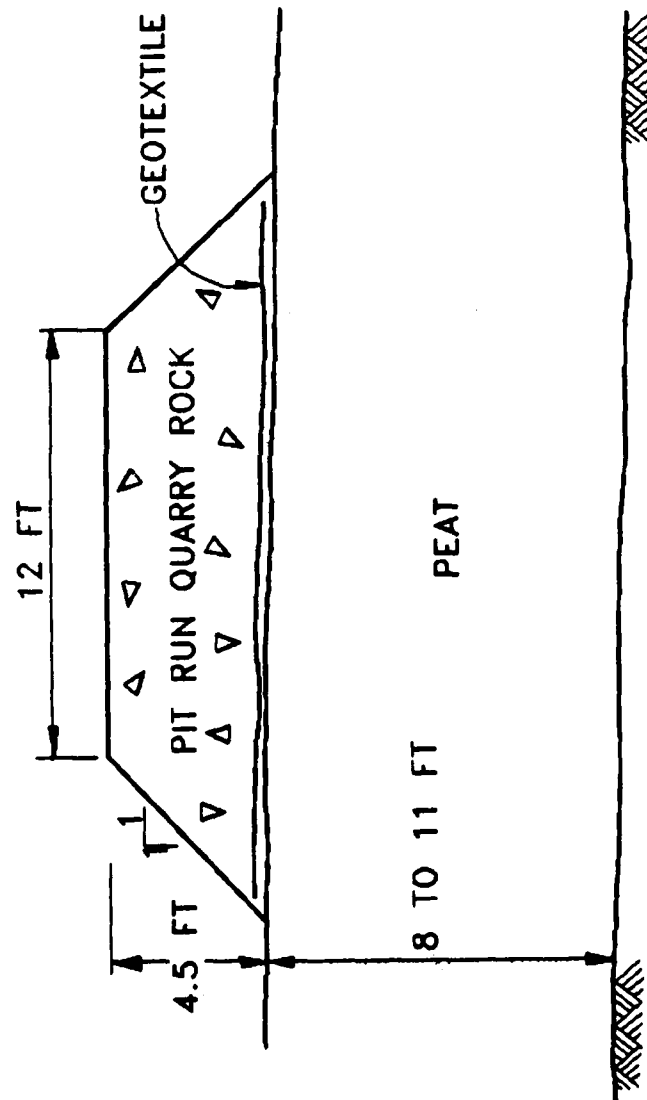
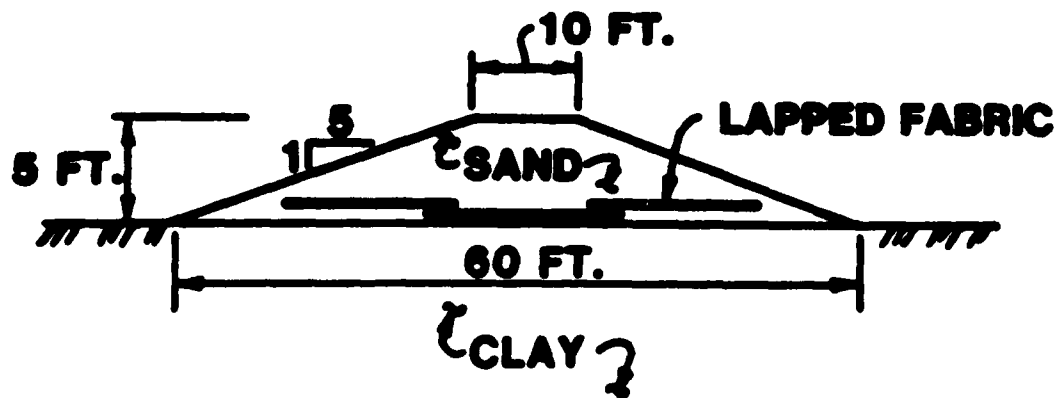


Figure 3. Typical section, geotextile reinforced embankment, Alaska.

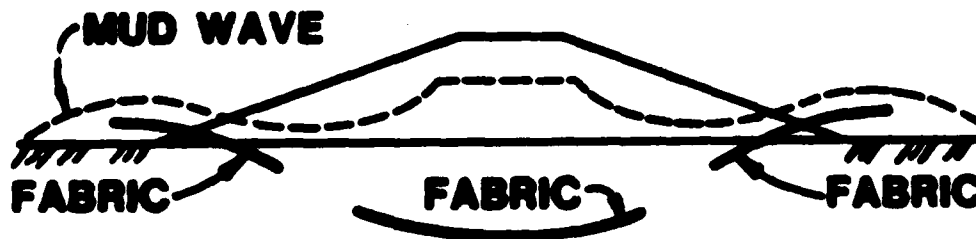
failure of the foundation. Where bearing capacity failures did not occur settlement of the embankment was essentially the same whether fabric reinforcement was used or not. They also found that settlement was independent of whether one or two layers of reinforcement were used in the embankment. It may be further concluded that the use of a high tensile modulus fabric would have been desirable. A high tensile modulus fabric would have developed high tensile stresses at low strains therefore, distributing the embankment weight over a larger area, reducing localized bearing failure.

Dredged Material Containment Dike, Brunswick, GA

18. The need for construction of a dredged material containment dike across very soft foundation material near Brunswick, Georgia, resulted in a recommendation for construction of a fabric reinforced embankment. A 3,000-ft long dredged material containment dike was proposed to be constructed about 5-ft high and 60-ft wide. The structure was to be raised by end dumping with single axial dump trucks hauling sand from a nearby dredged material disposal area. The geotextile reinforcement consisted of three 12-ft widths of a non-woven, heat bonded polypropylene fabric, weighing 4 oz/sq yd, placed along the center line of embankment over saw grass and a weeded surface. After the first roll was rolled out two additional widths of fabric were then placed parallel to the center line over lapping the first strip by about 3 ft on either side (see Figure 4). Additional construction procedures consisted of end dumping fill material along the center line of the embankment and spreading the fill outward toward the embankment toes. As construction progressed lateral and vertical earth pressure induce embankment spreading and subsidence creating mud waves which progressed forward and laterally. Construction was continued until approximately 95 percent embankment project length was achieved. At this point a catastrophic failure occurred when approximately 400 ft of the embankment failed. Efforts to repair this portion of the dike were excessive and extended beyond the project cost, therefore, the project was abandoned. Project failure was attributed to the fact that the fabric layers were unrolled and overlapped parallel to the alignment and during construction. Fabric on fabric slippage occurred creating discontinuity in the reinforcement. No resistance to lateral splitting was mobilized in the fabric



A. DESIGN



B. AFTER CONSTRUCTION

Figure 4. Fabric-reinforced embankment section, Brunswick, Georgia.

when the fabric layers separated, therefore, a foundation bearing failure occurred. It was concluded that the fabric layers should have been unroll transverse to the longitudinal alignment to enable the continuous fabric strips to resist the unbalance forces. Because the mud wave movements were not only lateral but also forward, overlapping the fabrics in a transverse direction probably would not have stayed in place but would have displaced forward providing a discontinuity in the reinforcement along the longitudinal axis. Therefore, it is recommended that all fabric strip should be sewn together in order to maintain reinforcement continuity in the transverse and longitudinal axis of the embankment.

Fabric Reinforced Embankment Swan Lake, Mississippi

19. A 1,600-ft long test section was constructed at Swan Lake, Mississippi for the purpose of determining the feasibility of constructing a fabric reinforced embankment on very soft backswamp deposits. The intended purpose for the embankment was to protect a game reserve from being flooded periodically by waters containing herbicides and pesticides from farming operations. Four 400-ft long, 80-ft wide, and 11-ft high test sections were constructed across an old oxbow lake filled with very soft clay deposits having an unconfined compressive strength of about 100 psf. Four separate test sections were constructed over varying depths of soft clay, underlain by sandy material. Plan and profile views of the four test sections with and without fabric reinforcement are shown in Figure 5. Test sections one and three consisted of non-woven needle punched fabric of two different weights, 8 oz/sq yd and 6 oz/sq yd, respectively. Test sections two and four were to be constructed without fabric and used as control sections. Each section was instrumented with vertical and horizontal slope inclinometers and open tube piezometers, which were monitored during and after construction. Prior to fabric placement the site was cleared by felling trees and covering the delimbed trunks and stumps with approximately 2 ft of lean clay material to form a working table. The fabric was placed transverse to the longitudinal axis of the embankment and all seams were sewn prior to placement of an additional foot of lean clay over the fabric in the central longitudinal portion of the embankment. The exposed fabric edges were then folded back over the previous placed material

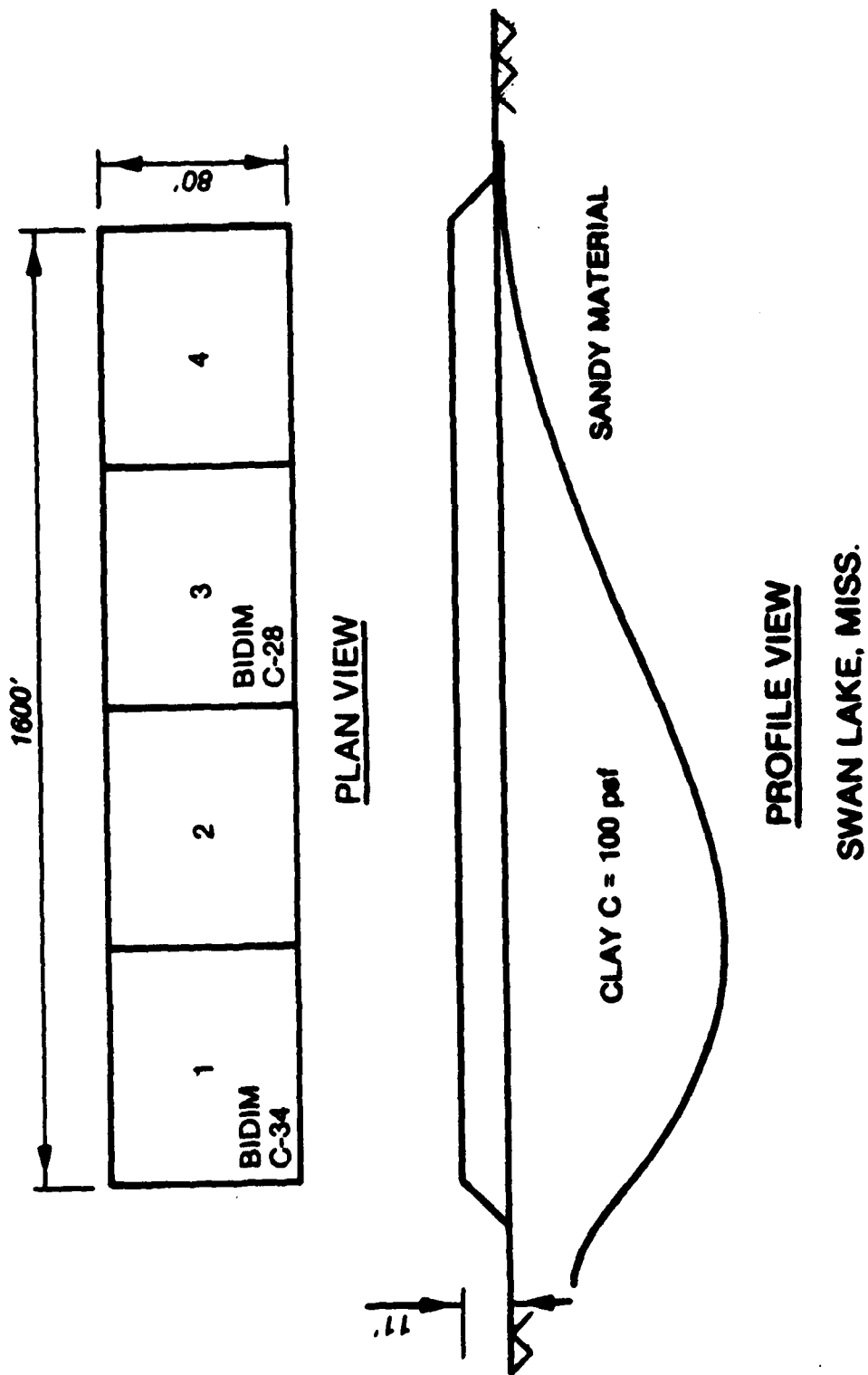


Figure 5. Plan and profile view of fabric-reinforced embankment at Swan Lake, Mississippi.

to prevent fabric slippage and to inhibit embankment spreading. A cross section of this design is shown in Figure 6. Dike construction was initiated at the end of test section four and progressed toward test section one. Since the initial portion of test section four was located on relative firm material equipment mobility problems were minimum and test section three and four were constructed to design height with minimum problems. About 12 hours after completion of test section three and four the embankment began to subside and spread laterally creating 6- to 12-in. wide longitudinal cracks along the embankments crest and slope. Embankment subsidence in test section one and three was relative rapidly with about 3- to 4-ft of vertical displacement and longitudinal cracks that appeared to be about 5- to 6-ft in depth. Dike construction at this point was not considered to be feasible and construction was terminated until the foundation materials could consolidate under embankment weight and support future construction activities. The two non-woven fabric reinforced test sections were excavated approximately one year after construction and it was discovered that the non-woven fabric had not failed by rupture as previously assumed but had undergone excessive elongation. During excavation of the two test sections it was found that the foundation at test section one had subsided a maximum of about 8.2 ft and the embankment had spread laterally up to about 13 ft. During excavation it was difficult to delineate the fabric location because the fabric offer practically no resistance to backhoe digging and it was difficult to determine the actual fabric location in the side of the trench. Figure 6 shows the location of the fabric and slope indicator pipe one year after construction. Observations made during embankment excavation at the two locations indicated that although the fabric had stretched up to about 36 percent it did not appear to be in tension near the embankment centerline or in the fabric folded back areas at the embankment toes. The fabric was found to be in the loose as place condition and was not acting as an anchor as originally assumed. It was postulated that the embankment failed by lateral spreading/splitting and excessive vertical displacement and creep. Because of the fact that little or no appreciable fabric tensile resistance was developed by the comparable weak fabric reinforces the need for the use of high tensile modulus, low elongation, and high ultimate strength fabrics in embankment reinforcement.

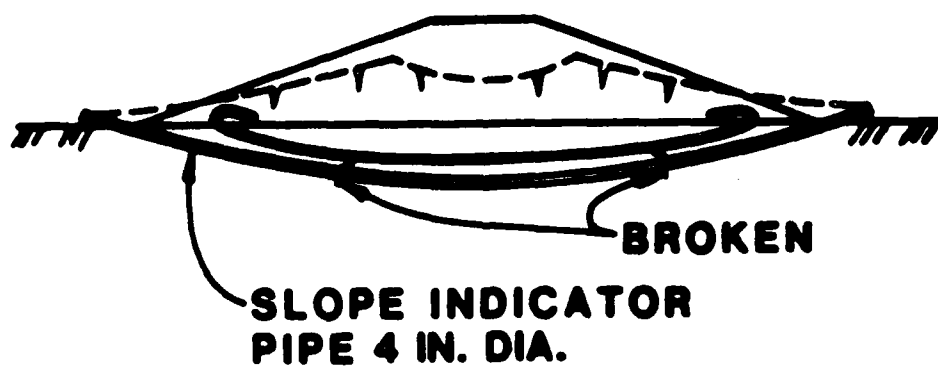
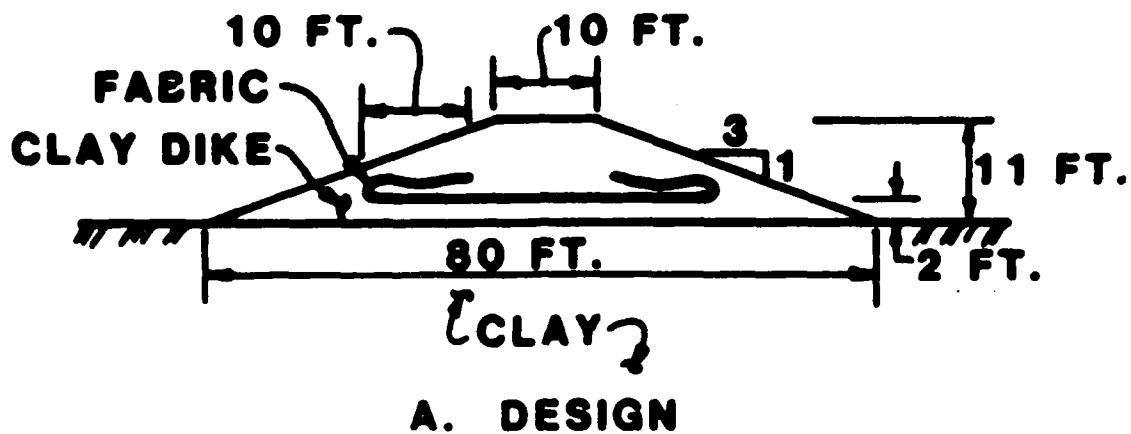


Figure 6. Fabric-reinforced embankment section, Swan Lake, Mississippi.

Fabric Reinforced Embankment Controlled Failure, Holland

20. In an effort to evaluate the possible function of a geotextile in an embankment constructed over a very soft foundation, four control fabric reinforced highway embankment test sections approximately 400-ft long by 160-ft wide with a one on one side slope were constructed in Holland. The embankments were constructed across very soft foundation material consisting of peat and clay to a depth of about 15 ft. Each of the test sections were instrumented with piezometers, settlement plates, and strain wires in an attempt to determine the reinforced embankment behavior. The 260-ft wide embankment had been constructed to about 8 ft above the foundation when a very shallow rotational slope failure occurred about 165-ft long and about 25-ft wide. The fabric that failed in this section had an ultimate tensile strength of about 250 lb/lin in. and was considered to be a high strength, high tensile modulus woven fabric. Figure 7 shows a plan view and cross sectional view of the embankment test section showing the failed areas. After embankment failure, a trench was excavated down through the fabric layer and observations showed that the fabric had torn and displaced downward approximately 3 ft. The fabric appeared to have been pulled into as though it had been placed in a uniaxial testing machine and pulled into tension. A conventional limited equilibrium rotational slope stability analysis indicated that the fabric reinforced section had a factor of safety slightly less than one at the time of failure. The results of this analysis proved and/or suggest that the use of conventional slope stability analysis to design geotextile reinforced embankment against rotational slope failure are satisfactory. Even though high strength and high modulus fabrics are available for use in fabric reinforced embankments the need still exist for proper embankment design and construction to prevent failure. The applicability of conventional slope stability concepts in fabric reinforcement embankment design, suggest that the design procedures used to reduce the chance of failure through the design of embankments with flatter slide slopes with berms can also be used to stabilize embankments.

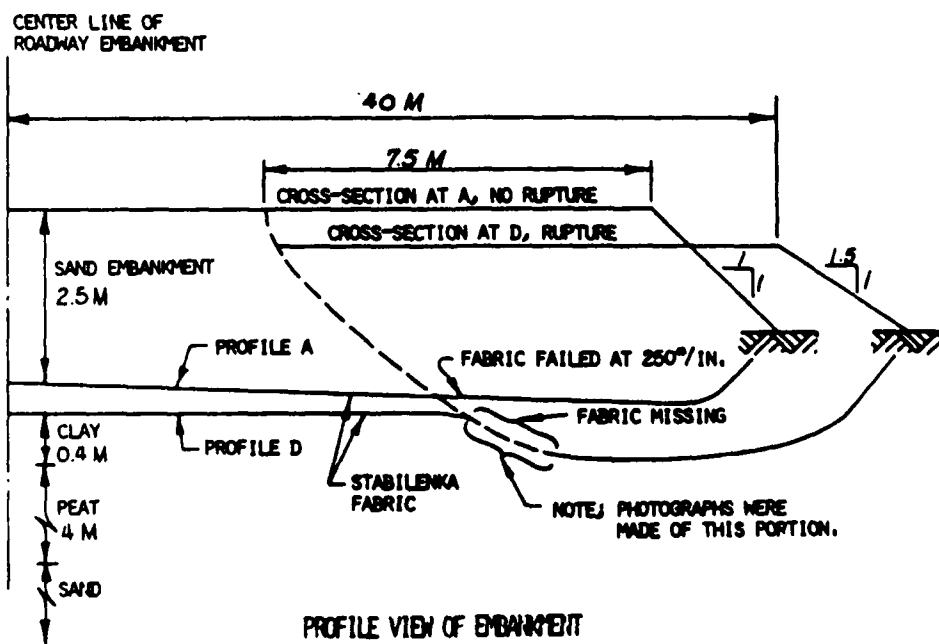
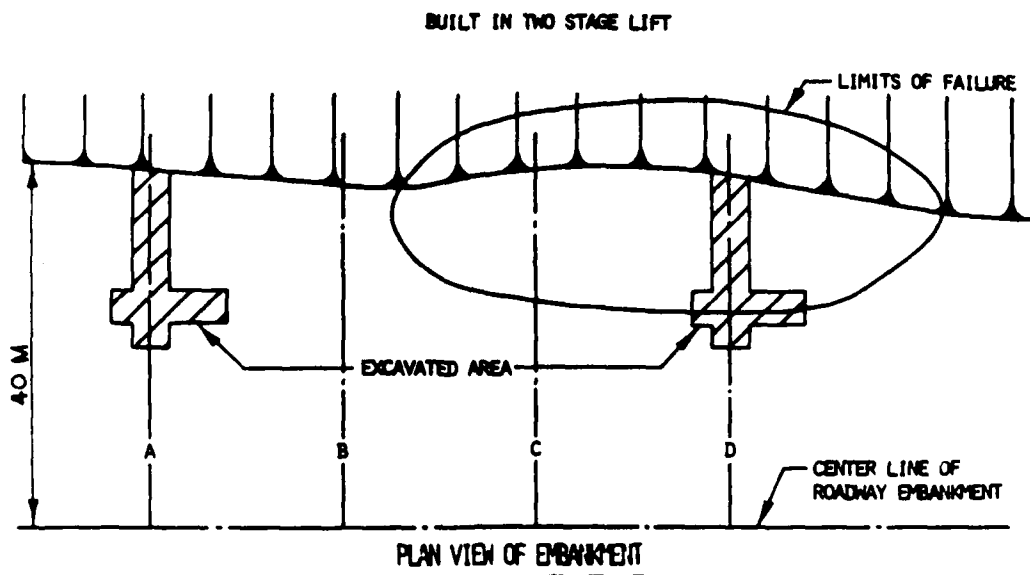
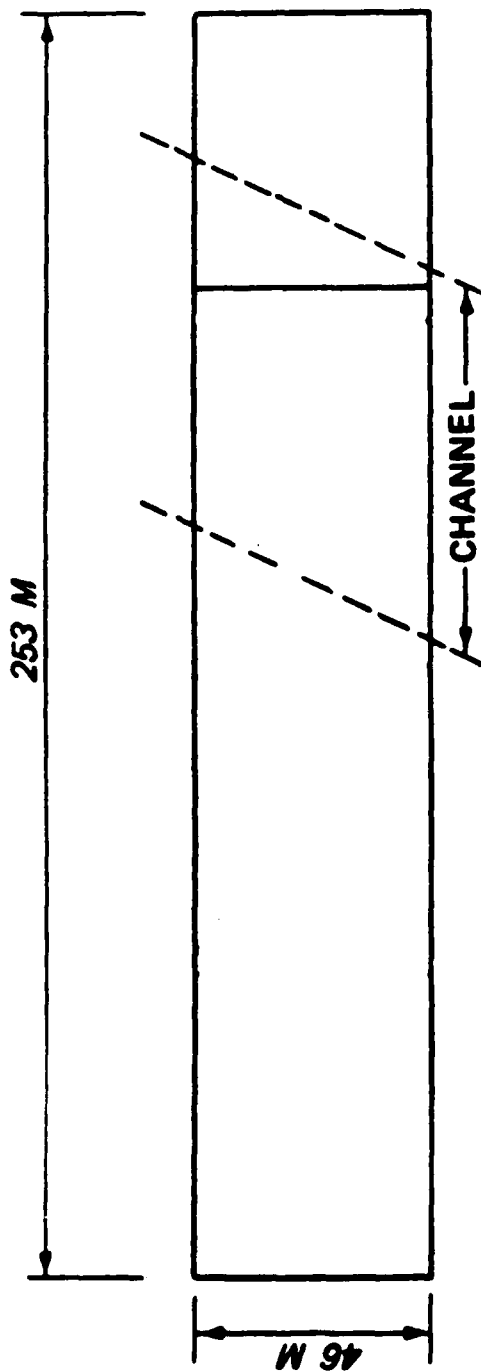


Figure 7. Plan and profile of embankment, Holland (Fowler and Haliburton, 1980).

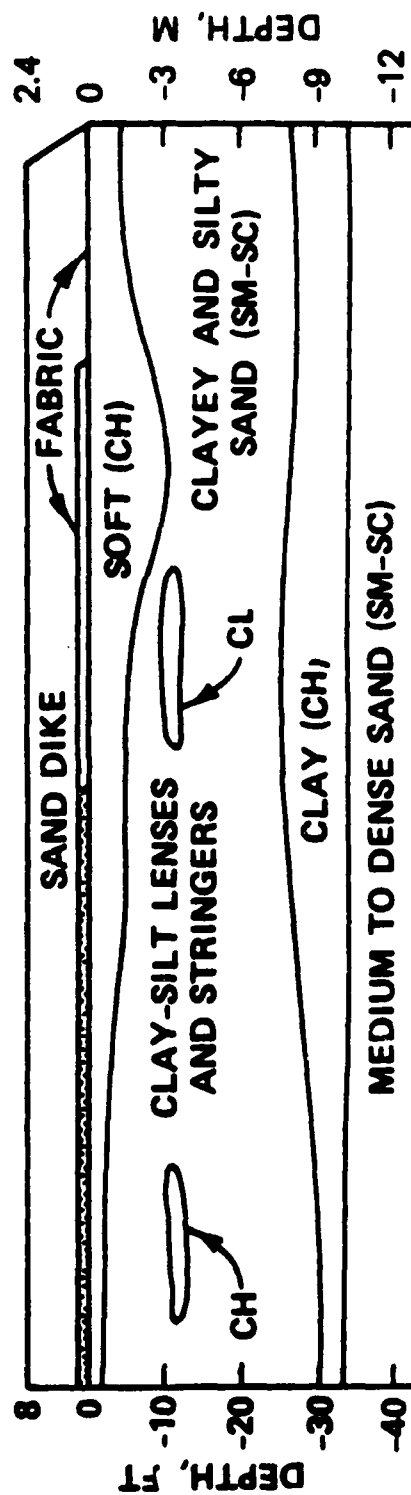
Fabric Reinforced Embankment, Pinto Pass, Mobile, Alabama

21. To provide a confined dredged material disposal area for Mobile Harbor, the US Army Corps of Engineers decided to construct a 6,000 ft, 8-ft high embankment on very soft soil with undrained shear strengths varying from 50 to a 150 psf. Over 50 percent of the proposed embankment alignment was located in the intertidal zone and a factor of safety of approximately 0.5 was found to exist for conventional embankment construction (Reference Fowler and Haliburton). After consideration of conventional construction alternatives of pre-loading, stage construction, and wide berms, the use of light weight fill material and construction of a displacement section it was decided to construct a 800-ft long, 8-ft high, 175-ft wide fabric reinforced embankment test section with 10 horizontal on 1 vertical slope. Fine grained, poorly graded dredged material sand was locally available for use as dike fill material. A plan view of the embankment test section and typical foundation soil profile are shown in Figure 8. The proposed embankment test section design determined that the geotextile properties required to resist lateral spreading and splitting, and embankment sliding, excessive displacement and a rotational slope failure. Fabric reinforced embankment design recommendations were as follows:

- a. Trail use of four high tensile, high modulus geotextile fabrics as reinforcement placed as shown in Figure 8.
- b. Specific construction procedures to ensure anchoring and pre-tension of the geotextile fabric during construction.
- c. Installation of settlement plates and piezometers to evaluate the behavior of the fabric reinforced embankment during and after construction. Even though minor problems occurred during construction the embankment was successfully constructed and no stability problems were encountered during or after construction. After evaluating the field data the following conclusions were:
 - (1) Proper embankment design and use of specified construction procedures were necessary for successful fabric reinforced embankment construction.
 - (2) Lateral spreading or splitting of the embankment can be held below 5.0 percent elongation with high tensile modulus fabric.
 - (3) Use of geotextile fabric as reinforcement in rapid embankment construction on soft foundations is a technically feasible and operationally practical and potentially cost effective construction alternative.



A. PLAN VIEW OF EMBANKMENT TEST SECTION



B. TYPICAL SOIL PROFILE, PINTO PASS, ALABAMA

Figure 8. Pinto Pass fabric-reinforced embankment plan view and foundation soil profile.

Fabric Reinforced Embankment, Craney Island, Norfolk District

22. The Craney Island Disposal Area is a 2,500 acre confined dredged material disposal site and is one of the largest dredged material containment area in the United States. The Corps of Engineers Norfolk District constructed the site in the '50s for long-term disposal of material dredged from ports and channels in the Hampton Road Area near Norfolk, Virginia. Almost continuous use for disposal from dredge pipeline discharge and hopper dredge pumpout has deposit over 180 million cu yds of material within the containment area. Attempts in the early '70s to construct two interior dike using wood debris and dump or hydraulic placed sand failed. The dikes were designed to create three subcontainment areas that would improve sedimentation in the containment area being used and allow the other two containment areas to dryout. Construction was halted when very soft dredged material was encountered about midway between the perimeter dikes, preventing the progression of end dumping and hydraulic placement. In order to subdivide the Craney Island Disposal Area into three compartments, the Norfolk District decided to construct a fabric reinforced embankment test section to determine the economic and construction feasibility of this relatively new construction technique. Extremely poor foundation conditions existed along the interior dike alignment for about 5,000 ft for closure of the north dike, and about 3,500 ft for the south division dike. Soft dredged material which extended to a depth of 30 to 40 ft at undrained shear strengths that ranged from about 25 to 100 psf. The predominate underlying in situ material was very soft marine clay CH and OH. The land surface enclosed by completion of perimeter dikes in 1957, was a -10 msl with the very soft marine clay extending to -90 msl. Approximately 40 percent of the dike alignment area had a 3- to 4-in.-thick dried crust. The other 60 percent was covered by recent deposits of dredged material and there was surface water ponded near the weirs. Site conditions dictated a wide shallow sloped dike (1 vertical: 10 horizontal) to be raised incrementally as filling of the containment area progressed. Previous experience indicated that the magnitude of dike displacement would be 8- to 10-volumes down for 1-volume above the surface of the dredged material. To provide the necessary initial containment area capacity the dike was to be 11 ft above present surface at

the embankment centerline. End dumping of displacement section is an acceptable method of dike construction where marginal foundation conditions exist. Clean sand dredged material was available at near by borrow sources but large quantities required to construct an unreinforced displacement section were not economically feasible. Also, engineering judgment led to the conclusion that it would be difficult if impossible to construct a controlled displacement dike section and achieve the desired width and stable base for future dike raisings anticipated at the Craney Island facility. A slope stability foundation analysis of the conventional dike construction without any reinforcement indicated that the factor of safety in bearing would be less than 1.0. Unreinforced dikes constructed on the soft foundation in the disposal area could exceed the foundation bearing capacity and result in one of the three types of failures or a combination of:

- a. Localized foundation failure with propagation of rotational failure through the dike.
- b. Lateral splitting or outward spreading and sliding of the dike.
- c. Bearing failure caused by excessive subsidence caused by excessive consolidation displacement and creep of the foundation materials.

Three fabric reinforced embankment test sections, 300-, 500-, and 750-ft long were successfully constructed on very soft dredged material deposits within the Craney Island dredged material containment area. Subsequently, two fabric reinforced dikes each about 4,000-ft long were constructed using this new and innovated construction technique to subdivide the 2,500 acre area into three separate areas to improve dredged material management. Successful completion of the three fabric reinforced dikes was a key element in the rapid implementation of the dredged material management program. The reinforced embankments were completed to design width and grade without excessive lateral spreading or rotational bearing failure in the foundation, despite excessive pore water pressure of about 20 ft, were developed above the dredged material surface.

Seagirt Project, Baltimore, Maryland

23. The Corps of Engineers was very fortunate to be allowed to monitor the constructed of the Seagirt project that was designed and constructed by the Maryland Port Administration, Baltimore, Maryland. This project was the

state of the art for soil stabilization using geosynthetic materials in 1986. The Seagirt project consisted of a 113-acre dredged material containment area that contained 18 ft of fine-grained dredged material 50 to 150 percent above the liquid limit of depths of 20 to 33 ft. This surface contained "alligator cracked crust" 1- to 4-in. deep on the ground surface allowing one to walk on most of the areas to be stabilized. This project provided design philosophy, construction methodology, and development of new and innovative materials that were being considered for the Wilmington, Delaware project. Rapid consolidation of soft, compressible, fine-grained soils by both radial and vertical drainage with plastic strip drains can effectively reduce the consolidation time by a factor 10. Penetration of the plastic strip drains on 5-ft centers through a sand blanket and high performance geotextile caused minimum damage to the performance properties of the fabric. A single layer of high performance geotextile with tensile strengths above 1,000 lb/lin in. and minimum thickness of sand placed directly on the fabric coupled with the use of low ground pressure equipment was the key element in the success of this project.

Wilmington, Delaware Strip Drain and Fabric

24. High strength geotextiles coupled with polymeric vertical strip drains were used beneath a 400- to 700-ft wide and 8,000-ft long dredged material containment dike constructed on a soft foundation adjacent to the Delaware River, Wilmington, Delaware, by the US Army Corps of Engineers, Philadelphia District. Plastic strip drains have virtually replaced the use of sand drain in consolidation of soft clay foundations throughout the world. Soft clay soils at the Wilmington project consisted of saturated fine-grained organic silts and clays with an undrained shear strength of less than 100 psf. These materials were typical of maintenance dredged materials that are dredged by the US Army Corps of Engineers from rivers, port facilities, and harbors. This project used the experience gained from the Seagirt project that was design and constructed by the Maryland Port Authority, Baltimore, Maryland. This project was heavily instrumented with piezometers, settlement plates, slope inclinometers and strain gages attached to the geotextiles. Laboratory tensile tests were conducted using strain gages attached to the geotextiles

and the results of the field and laboratory tests are being analyzed. Fill material was hydraulically placed on the geotextile as the geotextile was being placed in 2 to 7 ft of water from a 750-ft long line of barges. The completed dikes inclosed a 300-acre dredged material disposal area.

Fabric Reinforced Containment Dike, New Bedford Superfund Site

25. A 15-acre dredged material containment area was design and constructed using high performance geotextiles and plastic strips to consolidate the soft foundation clays beneath the dikes. The purpose of the dike was to contain PCB'S that were dredged from the New Bedford Harbor bottom. The dike was design in 1987 using some of the latest procedures developed by the US Army Corps of Engineers for fabric reinforced embankments on soft ground. Compatibility and strength tests were performed on one of the strongest fabrics ever woven in the US (i.e., tensile strength in excess of 5,000 lb/lin in. The dike was instrumented with slope inclinometers, settlement plates, piezometers, and stability poles. EP-series strain gages cemented to the embedded fabric indicated that loads on the fabric were within the range of values estimated during design. The dike's performance during the filling operation and 15 months after has been excellent. Significant cost savings were realized when comparing the fabric reinforced dike to other containment options.

Mohicanville

26. A 24-ft high, 1,100-ft long reinforced embankment successfully constructed by the US Army Corps of Engineers, Huntington District, on a very soft foundation that consisted of about 16 ft of peat and 60 ft of soft clay (see reference Fowler, Peters, Leach, and Horz). The embankment, which was a saddle dike for a flood reservoir, was constructed on a slope of 1 vertical and 3 horizontal with a clayey sand gravel fill. Conventional limited equilibrium and finite element analyses were conducted prior to construction to determine the necessary embankment tensile reinforcement to prevent potential failure (see Figure 9). Several analyses were conducted where woven polyester and Kevlar geotextiles were favorable considered but in the final analysis

welded steel wire mesh was selected because of the very high tensile modulus of the steel and the very low embankment movements allowed in the design. It was predicted from both conventional and finite analysis that varying the reinforcement modulus from low to high values significantly reduced the horizontal and vertical displacement of the embankment. More importantly, the high modulus was needed to ensure that the full working load would be developed in the reinforcement before mobilization of the foundation shear resistance. Loads measured in the steel wire mesh, pore pressure and settlement measurements in the embankment and foundation were within the values predicted during design and the finite element analysis. Successful completion of the embankment to design height would not have been possible without the use of high tensile modulus reinforcement.

Other Examples

27. A number of other very good examples and case histories that illustrate the use of geotextiles and welded wire to reinforced embankments on soft foundation have been published. Some of the earlier uses of geotextile for embankment reinforcement were three sites in Sweden. These sites were successfully stabilized with a woven polyester geotextile and the result of measurements during and after construction were described by Holtz (1975), Holtz and Massarsch (1976). Lukanen and Teig (1976), in the USA described the use of geotextiles and other reinforcement techniques involving corduroy construction for roadways winding through swamps in northern Minnesota. During the 1st International Conference on Geotextile in Paris, 1977, three fabric reinforced embankment test sections were reported. In an addition to the earlier case described by Bell, Greenway, and Vischer, 1977, full scale embankment tests were described by Belloni and Sembenelli, 1977, and Volman, Krekt and Risseeuw, 1977, there were several interesting case histories presented at the 2d International Conference on Geotextile in Las Vegas in 1982. These papers were by Brakel et al., 1982; Hannon, 1982; Barsvary, McLean, and Cragg, 1982; Olivera, 1982. All of these embankments were well instrumented and the authors concluded that the use of geotextiles definitely improved the stability of the embankment and in many cases analytical methods were presented and verified by the resulting instrumentation measurements.

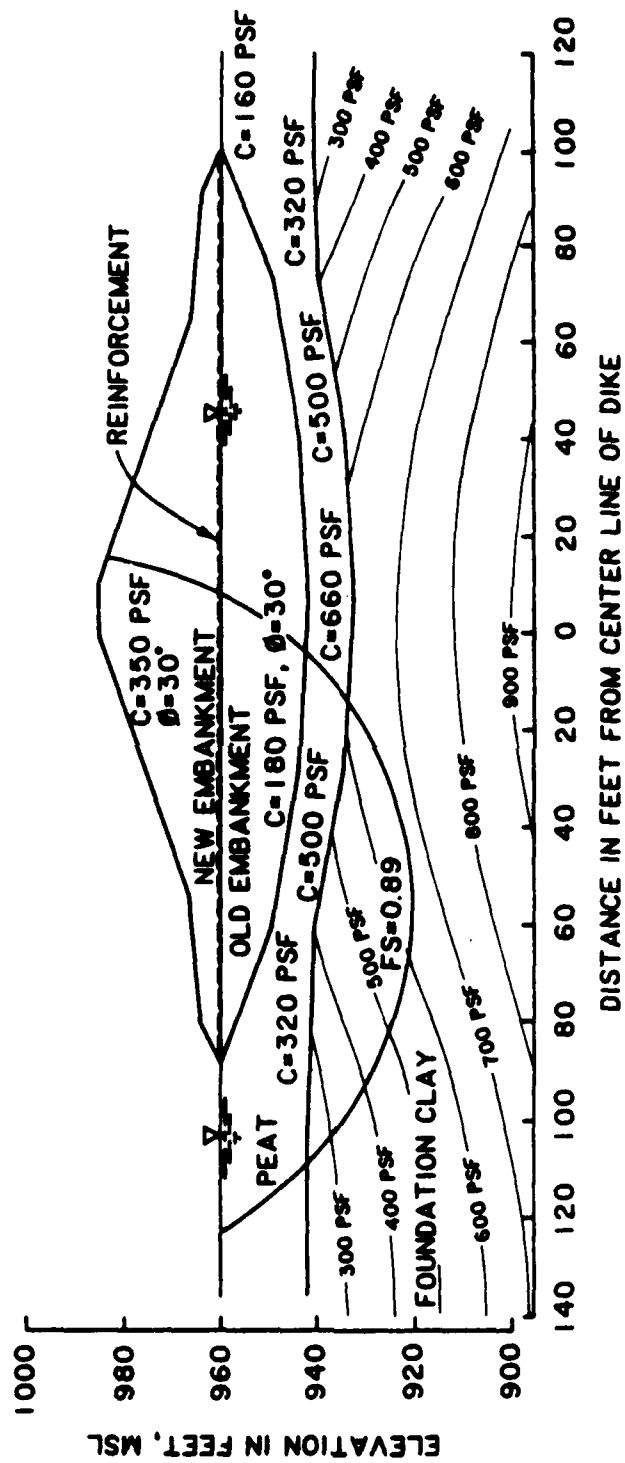


Figure 9. Mohicanville Dike No. 2. Limit equilibrium stability analysis.

PART IV: POTENTIAL EMBANKMENT FAILURE MODES

28. The design and construction of fabric-reinforced dikes on soft foundations have been found to be technically feasible, operationally practical, and cost effective when compared with conventional soft foundation construction methods and techniques. To successfully design a dike on a very soft foundation, three potential failure modes must be investigated.

- a. Horizontal sliding, splitting, or spreading.
- b. Rotational slope and/or foundation failure.
- c. Excessive vertical foundation displacement.

29. The fabric must resist the unbalanced forces necessary for dike stability and must develop moderate-to-high tensile forces at relatively low-to-moderate strains. It must exhibit enough soil-fabric resistance to prevent pullout. The fabric tensile forces resist the unbalanced forces, and its tensile modulus controls the vertical and horizontal displacement of dike and foundation. Adequate development of soil-fabric friction allows the transfer of dike load to the fabric. The development of tensile stresses prevent fabric pullout. Use of the proper construction sequence to develop fabric tensile stresses at small fabric elongations or strains is essential.

Horizontal Sliding, Splitting, and Spreading

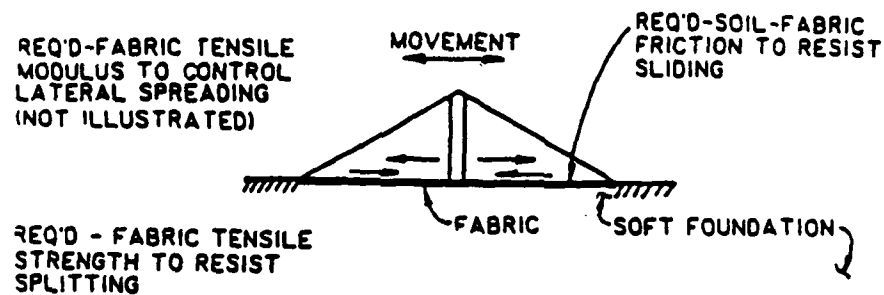
30. These types of failure of the dike and/or foundation may result from excessive lateral earth pressure (Figure 10a). These forces are determined from the dike height, slopes, and fill material properties. During conventional construction the dikes would resist these modes of failure through shear forces developed along the dike foundation interface. Where fabrics are used between the soft foundation and the dike, the fabric will increase the resisting forces of the foundation. Fabric-reinforced dikes may fail by fill material sliding off the fabric surface, fabric tensile failure, or excessive fabric elongation. These failures can be prevented by specifying the proper fabric that meets the required tensile strength, tensile modulus, and soil-fabric friction properties. Proper construction methods and techniques must be implemented so that these forces can develop.

Rotational Slope and/or Foundation Failure

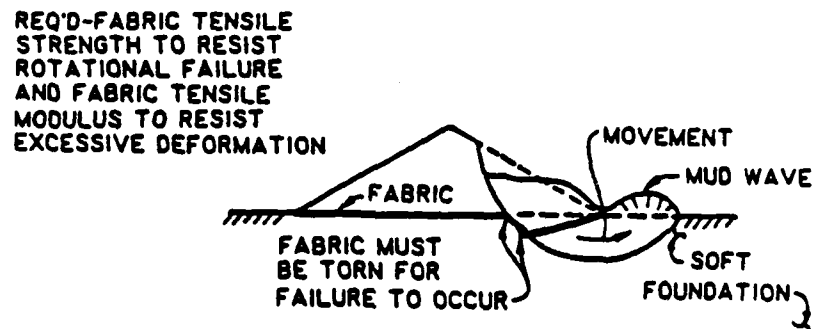
31. Fabric-reinforced dikes constructed to a given height and side slope will resist classic rotational failure if the foundation and dike shear strengths, plus the fabric tensile strength, is adequate (Figure 10b). The rotational failure mode of the dike can only occur through the foundation layer and fabric. For cohesionless fill materials, the dike side slopes are less than the internal angle of friction. Since the fabric does not exhibit flexural strength, it must be placed such that the critical arc determined from a conventional slope stability analysis intercepts the horizontal layer. Dikes constructed on very soft foundation will require high tensile strength fabrics to control the large unbalanced rotational moments.

Excessive Vertical Foundation Displacement

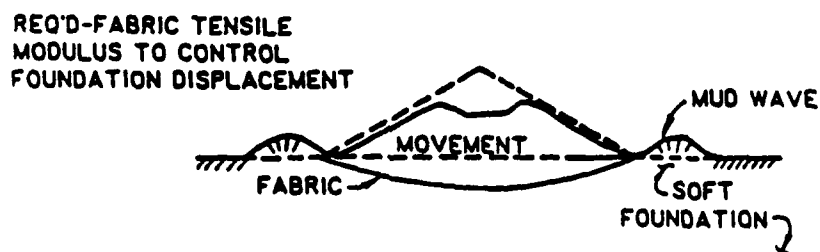
32. Consolidation settlements of dike foundations, whether fabric-reinforced or not, will be similar. Consolidation of fabric-reinforced dikes usually results in more uniform settlements than for non-reinforced dikes. Classic consolidation analysis is a well known theory, and foundation consolidation analysis for fabric-reinforced dikes seems to agree with predicted classical consolidation values. Soft foundations may fail partially or totally in bearing capacity before classic foundation consolidation can occur. One purpose of the fabric reinforcement is to hold the dike together until foundation consolidation and strength increase can occur. Generally, only two types of foundation bearing capacity failures may occur - partial or center-section foundation failure and rotational slope stability/foundation stability (previously discussed). Partial bearing failure, or "center sag" along the dike alignment (Figure 10c), may be caused by improper construction procedure, like working in the center of the dike before the fabric edges are covered with fill materials to provide a berm and fabric anchorage. If this procedure is used, fabric tensile forces are not developed and no benefit is gained from the fabric used. A foundation bearing capacity failure may occur as in conventional dike construction. Center sag failure may also occur when low-tensile strength or low-modulus fabrics are used, and embankment splitting occurs before adequate fabric stresses can be developed to carry the dike



a. POTENTIAL EMBANKMENT FAILURE FROM LATERAL EARTH PRESSURE



b. POTENTIAL EMBANKMENT ROTATIONAL SLOPE/FOUNDATION FAILURE



c. POTENTIAL EMBANKMENT FAILURE FROM EXCESSIVE DISPLACEMENT

Figure 10. Potential fabric-reinforced embankment failure modes.

weight and reduce the stresses on the foundation. If the foundation capacity is exceeded, then the fabric must elongate to develop the required fabric stress to support the dike weight. Foundation bearing capacity deformation will occur until either the fabric fails in tension or it carries the excess load. Low modulus fabrics generally fail because of excessive foundation displacement that occurs when these low tensile strength fabrics tend to elongate beyond their ultimate strength. This type of failure may occur where very steep dikes are constructed, and where out-side edge anchorage is insufficient.

PART V: OTHER CONSIDERATIONS IN FABRIC-REINFORCED
DIKE CONSTRUCTION

33. During conventional dike construction on soft foundation, poor mobility of construction equipment may prevent successful construction without dike failure. equipment mobility problems may be eliminated with low ground pressure equipment, properly selected fabrics, and when proper fill placement procedures are utilized. Fabric selection should not only be based on laboratory test performance properties but also on fabric workability, survivability, and constructability. Fabric field workability is directly related to fabric stiffness and whether the fabric is hydrophobic or hydrophilic. Where fabric is placed at or above the water table, a hydrophobic fabric is more desirable because it does not soak up water and become heavy and cumbersome to place. There is very little data on hydrophobic/hydrophilic properties of geotextiles, but generally polyethylenes and polypropylenes are hydrophobic and polyesters, arimid, and nybus are hydrophilic. Where a fabric is placed below water, a hydrophilic fabric is advantageous because it will sink. Fabrics with good field workability and high survivability will speed up dike construction. High survivability fabrics also reduce site preparation costs and survive contractor abuse during placement. Fabrics selected based on field workability and survivability may cost considerably more, but these costs may be outweighed by an increased rate of construction. Final fabric selection should always be based on a proper benefit-cost-ratio analysis.

34. Other considerations such as lime from natural limestone deposits affecting polyester fabric yarns is not true. Lime will affect polyester yarns but only at very high temperatures in the laboratory and not at ground temperatures.

Existing Fabric-Reinforced Embankment Design
Concepts and Geotextile Function

35. Existing Design Concepts. One of the first fabric-reinforced embankment designs constructed was by Dutch engineers in Holland. The design concept in the slope stability analysis considered only the fabric strength in the classic slope stability analysis and, therefore, did not consider all the

methods of analysis necessary for satisfactory embankment design. Fabric-reinforced embankments constructed on soft soil are normally divided into two areas-low embankments where live loads are relatively large and dead loads relatively small, and high embankments where the dead loads are large and the live loads relatively small, having little effect on stability. The function of the geotextile for low embankments is general for separation, with some consideration for reinforcement depending on its intended use. Low embankments are generally constructed without reinforcement, but subgrade performance under live loads may be unstable. In high embankments the geotextile function may be for separation during initial placement of the fill cover or working table, but the final function is for reinforcement. The rotational slope stability analysis is necessary to determine the fabric tensile strength, but the design must include an evaluation of fabric requirements for embankment splitting/spreading, sliding, and excess settlement. The limit equilibrium analysis is used to determine factor of safety and allows for better predictive behavior of the pore water pressure. The finite element analysis is used for settlement and stress analysis and stress-strain behavior of reinforcement. Finite element analysis is not recommended for design. Instead, a more simplistic approach, where lateral earth pressure, bearing capacity, and limit equilibrium slope stability analysis or wedge analysis should be used for determination of the reinforcement strengths and embankment deformation. Instrumentation readings have been taken during and after construction at several reinforced embankment test sections and the performance evaluation indicates the following:

- a. There was sufficient soil fabric friction to prevent sliding.
- b. Measured horizontal spreading of the embankment was very close to the predicted value.
- c. Fabric tensile strength in the warp direction was adequate to resist lateral spreading or splitting of the embankment.
- d. Where the geotextile tensile strength was sufficient, no rotational slope failure occurred.
- e. There was a minimum amount of vertical foundation displacement caused by the embankment.

36. These performance evaluations support the design procedure used to analyze lateral spreading, splitting, and sliding failure in addition to the

limit equilibrium rotational slope and foundation failure analysis. Splitting or tearing failure have occurred where embankments have been designed near a factor of safety of one. The close agreement between measurements made in the field and those predicted by the limit equilibrium analysis and the finite element analysis suggest that these design criteria techniques are satisfactory. Successful embankment construction is very dependent on the proper construction techniques as well as the proper design techniques.

37. Creep. Creep in geotextiles that have been loaded well beyond their recommended extensibility is a matter of concern, especially where these have been used for reinforcement of embankments on soft foundation. Geotextiles can be designed to resist creep if the working loads are kept well below the ultimate strength of the geotextile. The recommended working load should not exceed 25 percent of the ultimate load for polyethylene fabrics, 40 percent of the ultimate load for polypropylenes, and 50 percent of the ultimate fabric load for polyester fabric. Fabric creep will be kept to a minimum if the stress level or recommended working load is designed at or below the recommended percentages of the ultimate load for each type of polymer. When these design working loads are exceeded the fabric may continue to creep. If the consolidation and creep rate of the soil are faster than the creep rate of the fabric, continued elongation and movement of the embankment may occur. Where the consolidation and creep rate of the soil are faster than the creep rate of the fabric, the strength increase in the soil should exceed the strength lost in the geotextile. In some soils (such as peat, silt, and clays) primary consolidation may be rapid, but secondary consolidation could be very significant since it will occur over a long period of time. Design recommendations for creep properties will be discussed in detail later in this paper.

38. Fabric Anchorage Systems. A common failure mode for an embankment is by lateral spreading. Various construction techniques are used to prevent this lateral spreading, especially in very low embankments that are used for haul roads where the stresses along the wheel path and near the edges of the embankment toe are quite high. Figure 11 shows a number of these techniques that are used when insufficient anchorage is developed by a single layer of geotextile. These anchorage systems may not work for high embankments with less steep slopes since the stresses at the embankment toe are near zero, and are maximum along the embankment center line.

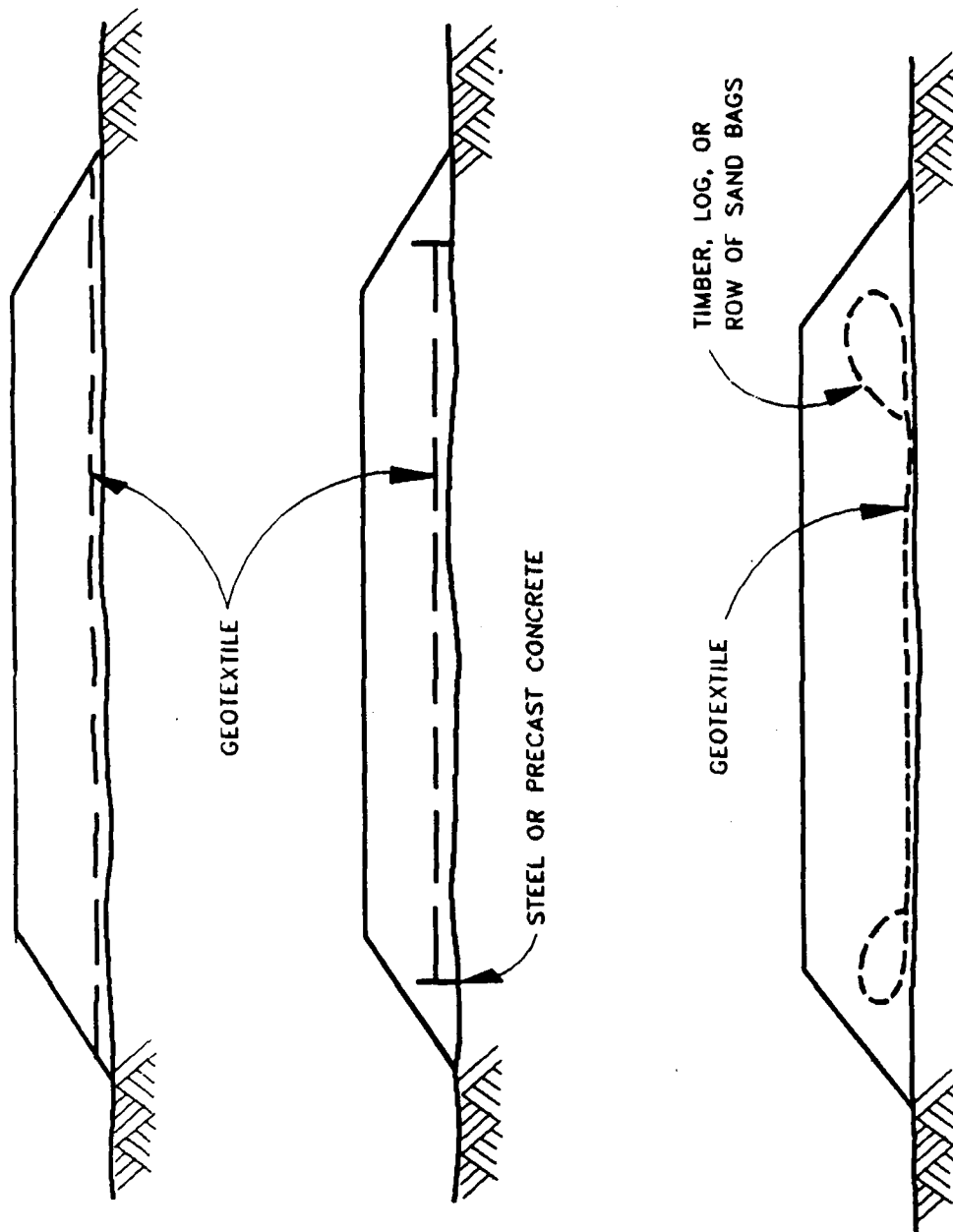


Figure 11. Concepts for using geotextiles to reinforce embankments on soft foundations.

39. Fabric Properties for Reinforcement Applications. There are four criteria for fabric reinforcement applications. These are constructability, durability, mechanical, and hydraulic properties. A description of each one is shown in Table 1 with a number of geotextile properties that are considered important. These design criteria and properties must be considered on a case by case basis. In most cases a complete set of mechanical tests will be needed to determine the necessary properties for design, depending on the nature of the project. Many of the geotextile tests may be conducted based on the designer's experience in the use of the geotextile selected. The fabric strength and modulus requirements should be based on wide-width tensile test results. In cases where very high strength fabrics (i.e., strengths greater than 1,000 lb/in.) are required, the wide-width test should be performed with 8-in. wide roller grips using test procedure described under ASTM D 4595.

40. Formation Soil Crust or Root Mat. Construction of embankments on very soft soil that has not formed a crust or root mat to support workmen or equipment has always been a construction problem in the past. Placement of a geotextile on these surfaces has allowed not only workmen to work safely but with the proper thickness of backfill material placed on these geotextiles will support the construction equipment. Where it is assumed the surface materials may squeeze out foundation material below the geotextile and cause a drag force on the underneath side of the fabric, then the number of fabric panels placed on the surface needs to be limited. The number of panels is generally governed by the available seams strength connecting the panels. The applied force is determined from the width of panel and not less than one-half of the strength of the surface materials.

41. Recommended Criteria. A number of analytical procedures using the finite element method of analysis have been proposed, but none have been developed to the point of practical use. Even though the predicted results from the finite element analysis and the measurements made in the field are usually in close agreement, it is not recommended for design purposes. The finite element analysis is recommended only to give the design engineer an indication as to locations and ranges of values for instrumentation in the embankment.

Table 1
Important Criteria and Properties - Reinforcement Applications

<u>Criteria</u>	<u>Property*</u>
Constructability	Strength Temperature Stability Ultraviolet Light Stability Wetting and Drying Stability Flammability Thickness Water Absorption Puncture Resistance Tear Resistance Cutting Resistance Modulus
Durability	Ultraviolet Light Stability Temperature Stability Chemical Resistance Wetting and Drying Stability Biological Resistance
Mechanical	Tensile Strength Modulus - Static Modulus - Dynamic Friction/Adhesion Fatigue Creep - Static Creep - Dynamic Seam Strength
Hydraulic	Thickness Permeability EOS/AOS

* All may not be important for every application.

Bell, J. R., Hicks, R. G., et al., (1980) "Evaluation of Test Methods and Use Criteria for Geotechnical Fabrics in Highway Applications," Oregon State University, Corvallis, Report No. FHWA/RD-80/021.

The limit equilibrium analysis is recommended for design of geotextile-reinforced embankments because of the cost and complexity of the finite element method. These analytical procedures are quite similar to conventional bearing capacity or slope stability analysis. Even though the rotational stability analysis assumes that ultimate fabric tensile strength will occur instantly to resist the active moment, some fabric strain, and consequently embankment displacement, will be necessary to develop tensile stress in the geotextile. The amount of movement within the embankment may be limited by the use of high tensile modulus fabric that exhibits good soil-fabric frictional properties. Conventional slope stability analysis assumes that the fabric reinforcement acts as a horizontal force to increase the resisting moment. The following analytical procedures should be conducted for the stability analysis of a geotextile-reinforced embankment:

- a. Overall bearing capacity.
- b. Edge bearing capacity or slope stability.
- c. Sliding wedge analysis for embankment spreading/splitting.
- d. Analysis to limit geotextile deformation.
- e. Determine fabric strength in a direction transverse to the longitudinal axis of the embankment or the longitudinal direction of the geotextile.

In addition, embankment settlements and creep must also be considered in the overall analysis.

42. Overall Bearing Capacity. The overall bearing capacity of an embankment must be determined whether or not geotextile reinforcement is used. If the overall stability of the embankment is not satisfied, then there is no point in reinforcing the embankment unless a fabric-soil displacement section is desired. Several bearing capacity procedures are given in standard foundation engineering textbooks. Bearing capacity analyses follow classical limiting equilibrium analysis for strip footings, using assumed logarithmic spiral or circular failure surfaces. Another bearing capacity failure is the possibility of lateral squeeze or creep of the underlying soils. Therefore, the lateral stress and corresponding shear forces developed under the embankment should be compared with the sum of the resisting passive forces and the product of the shear strength of the soil failure plane area. If the overall bearing capacity analysis indicates an unsafe condition, stability can be improved by adding berms or by extending the base of the embankment to provide a

wide mat, thus spreading the load to a greater area. These berms or mats may be reinforced by properly designing geotextiles to maintain continuity within the embankment to reduce the risk of lateral spreading or splitting.

43. Slope Stability Analysis. If the overall bearing capacity of the embankment is determined to be satisfactory, then the rotational failure potential should be evaluated with conventional limit equilibrium slope stability analysis or wedge analysis. The potential failure modes for a circular arc analysis are shown in Figure 12. The circular arc method simply adds the strength of the fabric layers to the resistance forces opposing rotational sliding because the fabric must be physically torn for the embankment to slide. This analysis consists of determining the most critical failure surfaces, then adding one or more layers of geotextile at the base of the embankment with sufficient strength at strain levels acceptable to the designer to provide the necessary resistance to prevent failure at an acceptable factor of safety. There are a number of computerized rotational stability analyses that require very minimal effort to properly analyze an embankment. Depending on the nature of the problem, a wedge-type slope stability analysis may be more appropriate. The analysis may be conducted by accepted wedge stability methods, where the fabric is assumed to provide horizontal resistance to outward wedge sliding and solving for the fabric tensile strength necessary to give the desired factor of safety. The critical slip circle or potential failure surfaces can be determined by conventional geotechnical limited equilibrium analysis methods. These methods may be simplified by the following assumptions:

- a. Soil shear strength and fabric tensile strength are mobilized simultaneously.
- b. Because of possible tensile crack formations in a cohesionless embankment along the critical slip surface, any shear strength developed by the embankment (above the fabric) should be neglected.
- c. The critical slip circles will be the same for both the fabric-reinforced and non-reinforced embankments.

44. Under these conditions, a stability analysis is performed for the no-fabric condition, and a critical slip circle and minimum factor of safety is obtained. A driving moment or active moment (AM) and soil resistance moment (RM) are determined for each of the critical circles. If the factor of

FS = SAFETY FACTOR

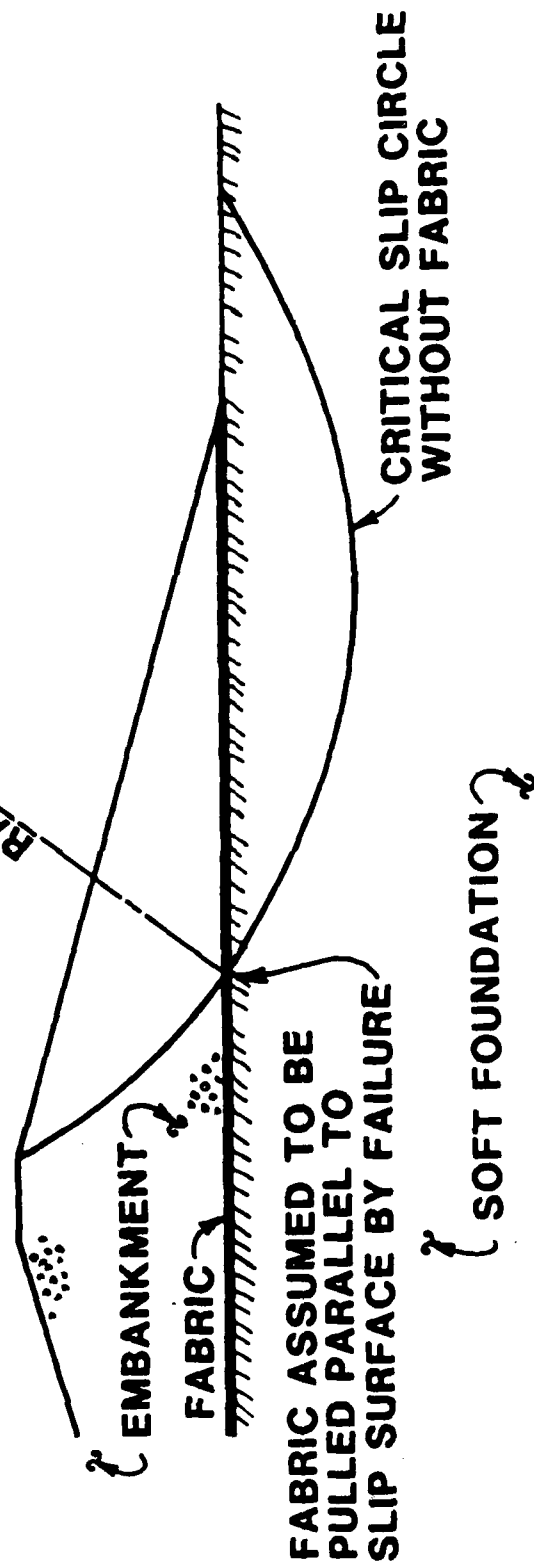
AM = ACTIVATING MOMENT

RM = SOIL ONLY RESISTING MOMENT

**T = REQ'D FABRIC TENSILE
STRENGTH**

$$FS = \frac{RM + T \cdot R}{AM}$$

$$T = \frac{AM(FS) - RM}{R}$$



METHOD OF DETERMINING FABRIC STRENGTH TO PREVENT SLOPE FAILURE

Figure 12. Concept used for determining fabric tensile strength necessary to prevent slope failure.

safety without fabric is inadequate, then an additional reinforcement resistance moment can be computed as follows:

$$TR + RM/FS = AM \quad (\text{Eq 1})$$

45. This concept is illustrated in Figure 12. The geotextile reinforcement T can be determined to provide the necessary resisting moment and required factor of safety. A common error in this equation is to apply the factor of safety to the active moment (AM).

46. There are a number of analytical procedures for determining the required geotextile reinforcement. Before a design is finalized, one or more independent procedures should be compared with the basic design calculations. The primary difference between the methods is how the effect of reinforcement is considered in the stability analysis. Most consider that the geotextile provides an additional resisting moment equal to the fabric strength T becomes the vertical distance R_y from the horizontal X-plane of the fabric to the center of rotation, rather than using the radial distance to the center of the circle of the critical arc. The additional resisting moment is expressed as:

$$\Delta M_r = T \times R_y \quad (\text{Eq 2})$$

47. Another method considers an additional resisting moment calculated from the vertical component (due to the soil fabric interaction):

$$\Delta M_r = T \times R_y + T_f \times R_x \tan \phi \quad (\text{Eq 3})$$

48. Each of these methods requires that the depth of the critical failure circle be relatively shallow; otherwise, the contribution of the geotextile to the resisting moment will be small. One particular method assumes that the geotextile reinforcement would be equivalent to the strength of a thin cohesive soil layer uniformly distributed along the failure plane or critical arc. This additional strength is expressed as follows:

$$\Delta M_r = T \times R \quad (\text{Eq 4})$$

This last method is less conservative than the others, which generally required a much weaker geotextile.

49. Sliding Wedge Analysis. The forces involved in an analysis for embankment sliding are shown in Figure 13. These forces consist of an actuating force composed of lateral earth pressure and a resisting force created by frictional resistance between the embankment fill and geotextile. To provide the adequate resistance to sliding failure, the embankment side slopes may have to be adjusted, and a proper value of soil-fabric friction needs to be selected. Lateral earth pressures are maximum beneath the embankment crest. The resultant of the acting earth pressure per unit length (P_A) for the given cross section may be calculated as follows:

$$P_A = 0.5 \gamma_m H^2 K_A \quad (\text{Eq 5})$$

where

γ_m = embankment fill compacted density force per length cubed, or F/L^3

H = maximum embankment height

K_A = coefficient of active earth pressure (dimensionless)

For a cohesionless embankment fill, the equation becomes:

$$P_A = 0.5 \gamma_m H^2 \tan^2(45 - \phi/2) \quad (\text{Eq 6})$$

Resistance to sliding may be calculated per unit length of embankment as follows:

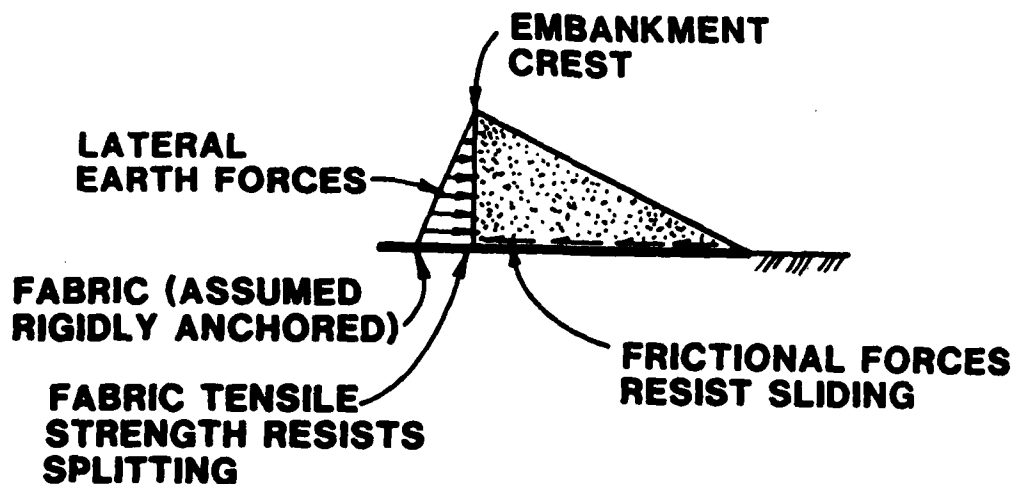
$$P_R = 0.5 \gamma_m X H^2 \tan \phi_{SF} \quad (\text{Eq 7})$$

where

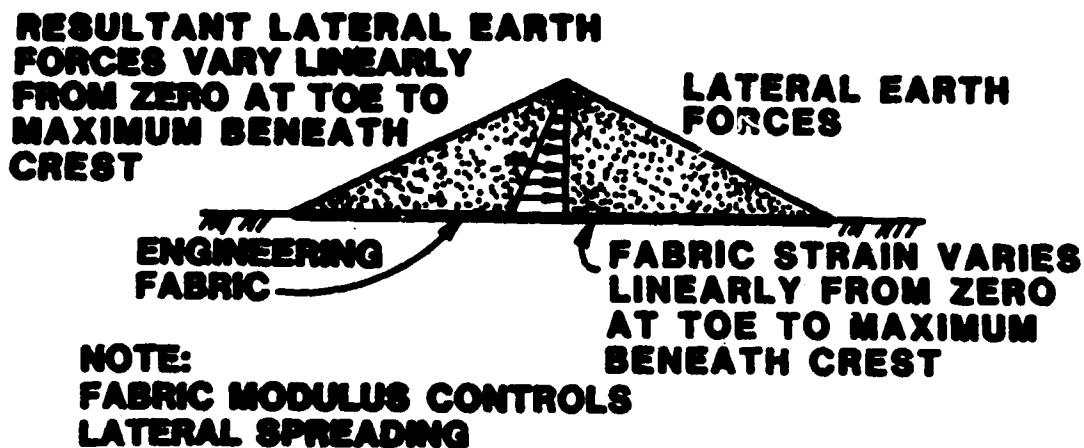
P_R = resultant of resisting forces (F/L)

X = dimensionless slope parameter (i.e., for 3H on 1V slope, $X = 3$)

ϕ_{SF} = soil-fabric friction angle (deg)



FORCES INVOLVED IN SPLITTING AND SLIDING ANALYSES



FABRIC STRAIN CHARACTERISTICS RELATING TO EMBANKMENT SPREADING ANALYSIS

Figure 13. Assumed stresses and strains related to lateral earth pressures.

A factor of safety against embankment sliding failure may be determined by taking the ratio of the resisting forces to the actuating forces. For a given embankment geometry the factor of safety is controlled by the soil-fabric friction. A minimum factor of safety of 2.0 is recommended against sliding failure. By combining the previous equations with a factor of 2.0, and solving for ϕ_{SF} gives the following equation:

$$\phi_{SF} = \tan^{-1} FS/X \tan^2 (45^\circ - \phi/2) \quad (\text{Eq } 8)$$

If it is determined that the required soil-fabric friction angle exceeds what might be achieved with the soil and fabric chosen, then the embankment side slopes must be flattened, or additional berms may be considered. Most high-strength geotextiles exhibit a fairly high soil-fabric friction angle (ϕ_{SF}) that is equal to or greater than 30 deg, where loose sand-size fill material is utilized. Assuming that the embankment sliding analysis results in the selection of a geotextile that prevents embankment fill material from sliding along the fabric interface, then the resultant force because of lateral earth pressure must be less than the tensile strength at the working load of the geotextile reinforcement. For a factor of safety of 1.0, the tensile strength would be equal to the resultant of the active earth pressure per unit length of embankment. A minimum factor of safety of 1.5 should be used for the geotextile to prevent embankments splitting, spreading, and/or tearing. Therefore, the minimum required fabric tensile strength is:

$$T_F = 1.5 P_A \quad (\text{Eq } 9)$$

where T_F = minimum fabric tensile strength (F/L).

50. Embankment Spreading Failure Analysis. Fabric tensile forces necessary to prevent lateral splitting or spreading failure are not developed without some fabric strain in the lateral direction of the embankment. Consequently, some lateral movement of the embankment must be expected. Figure 13 states the assumed fabric strain distribution that will occur from incipient embankment spreading if it is assumed that strain in the embankment varies linearly from zero at the embankment toe to a maximum value beneath embankment

crest. Therefore, a factor of safety of 1.5 is recommended in determining the minimum required fabric tensile modulus. If the geotextile tensile strength (T_F) determined by Equation 9 is used to determine the required tensile modulus (E_F), a factor of safety of 1.5 will be automatically taken into account, and the minimum required fabric tensile modulus may be calculated as follows:

$$E_F = T_F / \epsilon_{\max} \quad (\text{Eq 10})$$

where ϵ_{\max} = maximum strain which the fabric is permitted to undergo at the embankment center line. Assuming the strain distribution described in Figure 13, then the maximum fabric strain is equal to twice the average strain over the embankment width. A reasonable limiting value of 2.5 percent for lateral spreading is satisfactory from a construction and fabric property standpoint. This value should be used in design but depending on the specific project requirements larger strains may be specified. Assuming that 2.5 percent is the average strain, then the maximum strain which would occur is 5 percent. Replacing ϵ_{\max} in Equation 10 with 0.05 provides the required fabric tensile modulus as follows:

$$E_F = 20 T_F \quad (\text{Eq 11})$$

51. Potential Embankment Rotational Displacement. It is assumed that the fabric ultimate tensile resistance is instantaneously developed to prevent rotational slope/foundation failure and is inherently included in the slope stability limit equilibrium analysis. But for the fabric to develop tensile resistance, the fabric must strain in the vicinity of the potential failure plane. To prevent excessive rotational displacement, a high-tensile-modulus fabric should be used. Therefore, until more is learned about this particular failure mechanism, the following assumptions should be made concerning geotextile behavior:

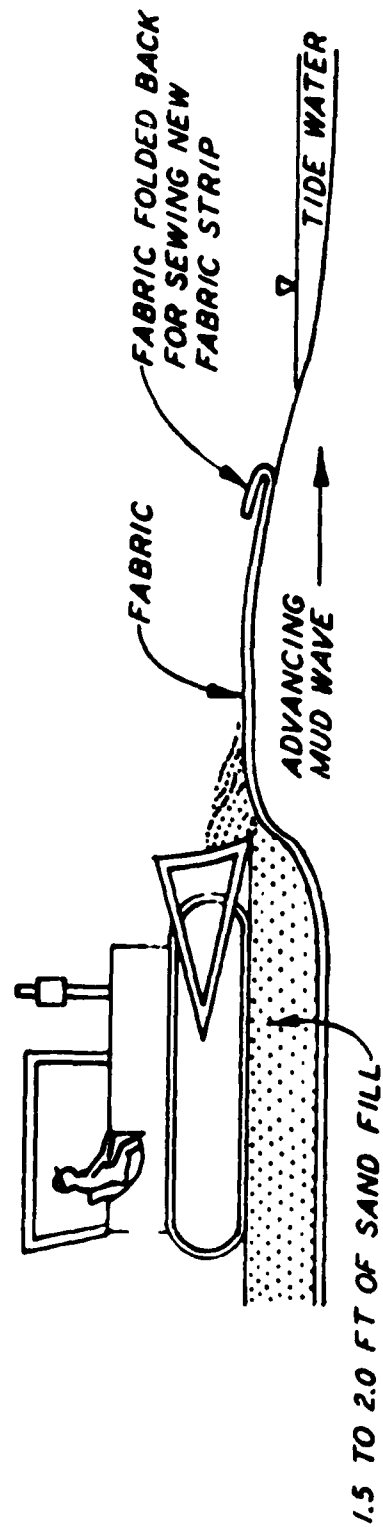
- a. The fabric located in the sliding wedge cannot physically pull out "around the corner," thus, it is assumed to be rigidly embedded in the wedge (Figure 12).
- b. Behavior of the fabric remaining in the center intact portion of the embankment will be similar to that encountered in pull-out resistance testing.

- c. The fabric is rigidly anchored (by opposing forces/strains of similar nature) at the embankment center line.
- d. A limiting average fabric strain of 5 percent over the interval between the center line and the intersection of the critical slip circle with the fabric layer appears to be acceptable. Therefore, the minimum required fabric tensile modulus to limit or control incipient rotational displacement is:

$$E_{FR} = T_F / 0.05 = 20 T_F \quad (\text{Eq 12})$$

52. Longitudinal Fabric Strength Requirements. Fabric strength requirements must be evaluated and specified for both the transverse and longitudinal direction of the embankment. Fabric stresses in the warp direction of the fabric or longitudinal direction of the embankment result from foundation movement where soils are very soft and create wave or a mud flow that drags on the underside of the fabric. The mud wave not only drags the fabric in a longitudinal direction but also in a lateral direction toward the embankment toes. By knowing the shear strength of the mud wave and the length along which it drags against the underneath portion of the fabric, then the spreading force induced can be calculated. Forces induced during construction in the longitudinal direction of the embankment may result from the lateral earth pressure of the fill being placed. These loads can be determined by the methods described earlier where $T_F = 1.5 P_A$, and $E_F = 20 T_F$ at $\epsilon = 5$ percent. The fabric strength required to support the height of the embankment in the direction of construction must also be evaluated. The maximum load during construction includes the height or thickness of the working table, the maximum height of soil dumped by dump trucks, and the equipment live and dead loads. The fabric strength requirements for these construction loads must be evaluated using the methods discussed in previous sections. Figure 14 illustrates the loads that are imposed by movement of a mud wave beneath the fabric, caused by the construction equipment and the thickness of the working table.

53. Embankment Deformation. A primary purpose of geotextile reinforcement in an embankment is to reduce the vertical and horizontal deformations. The effect of this reinforcement on horizontal movement in the embankment spreading modes has been addressed previously. One of the more difficult tasks is to estimate the deformation or subsidence caused by consolidation and



SOFT FOUNDATION

LAYING FABRIC ON MUD WAVE

Figure 14. Illustration of mud wave formation in a fabric-reinforced embankment.

by plastic flow or creep of the very soft foundation materials. Elastic deformations are a function of the subgrade modulus. The presence of a geotextile increases the overall modulus of the reinforced embankment. Since the lateral movement is minimized by the geotextile, the applied loads to the soft foundation materials are similar to the applied loads in a laboratory consolidation test. Therefore, for long-term consolidation settlements beneath fabric-reinforced embankments, the compressibility characteristics of the foundation soils should not be altered by the presence of the reinforcement. Finite element studies indicate a slight reduction in total settlement for a reinforced embankment but no significant improvement. Other studies indicate that very high-strength, high-tensile modulus geotextiles can control foundation displacement during construction, but the methods of analysis are not as well established as those for stability analysis. Therefore, if the embankment is designed for stability as outlined previously, then the lateral and vertical movements caused by subsidence from consolidation settlements, plastic creep, and flow of the soft foundation materials will be minimized.

54. Factor of Safety. The factor of safety used depends largely on the intended use of the structure, consequences of failure, and the limitations of the subsurface geotechnical investigation that was conducted. A factor of safety of 1.5 is recommended for embankments constructed on soft foundation. For bearing capacity of strip footings, an N_c value of 3.5 is used for very soft foundations (shear strength less than 200 psf), and an N_c of 5.14 is used for soft foundations. There has been considerable discussion as to the choice of an appropriate factor of safety for construction with geotextiles, especially when the calculated factor of safety without geotextiles is significantly less than unity. In most designs, geotextiles are not considered until the factor of safety is less than one. For designs where the factor of safety is greater than one, the fabric acts as second line of defense against failure. For designs where the factor of safety without geotextiles is significantly less than one, the geotextile reinforcement may be the difference between success and failure. The factor of safety should not only be based on the ultimate strength of the fabric but also on its working load, depending on the type of polymer used to manufacture the fabric as discussed in previous paragraphs. Factors of safety of 1.3 for slope/foundation rotational failures, 1.5 against lateral splitting and/or spreading failure, 2.0 against

sliding, and 1.3 against excessive rotational displacement are recommended in fabric-reinforced geotextile designs.

Example of Fabric-Reinforced Embankment Design

55. The Assumption.

- a. Pinto Pass Test Section Embankment, Mobile, Alabama, fill material consisting of clean sand with $\gamma_m = 100$ pcf, and $\phi = 30$ deg.
- b. Foundation properties (unconsolidated, undermined shear strength) as shown in Figure 15 (water table at surface).
- c. Embankment dimensions (Figure 15).
 - (1) Crest width of 12 ft.
 - (2) Embankment height (H) of 7 ft.
 - (3) Embankment slope, 10H on 1V (i.e., $x = 10$).

56. The Specifications Required. The original project was a dredged material containment site, and the test section design was the first fabric-reinforced embankment designed and constructed by the Corps of Engineers. The project being experimental, a localized failure could occur without significant damage, but a factor of safety of 1.3 was chosen for rotational slope failure during the original design. This design example will also consider a factor of safety of 1.3 against rotational slope failure, 1.5 against spreading/splitting, 2.0 against sliding failure, and 1.3 against excessive rotational displacement for the geotextile fabric requirements. Prepare minimum fabric specifications.

57. The Solution. Calculate overall bearing capacity:

- a. Ultimate bearing capacity q_{ult} for strip footing on clay.

$$q_{ult} = cN_c = (75)(5.14) = 385 \text{ psf (with surface crust)}$$

$$q_{ult} = cN_c = (75)(3.5) = 263 \text{ psf (without surface crust)}$$

It has been found from experience that excessive mud wave formation is minimized when a dried crust has formed on the ground surface.

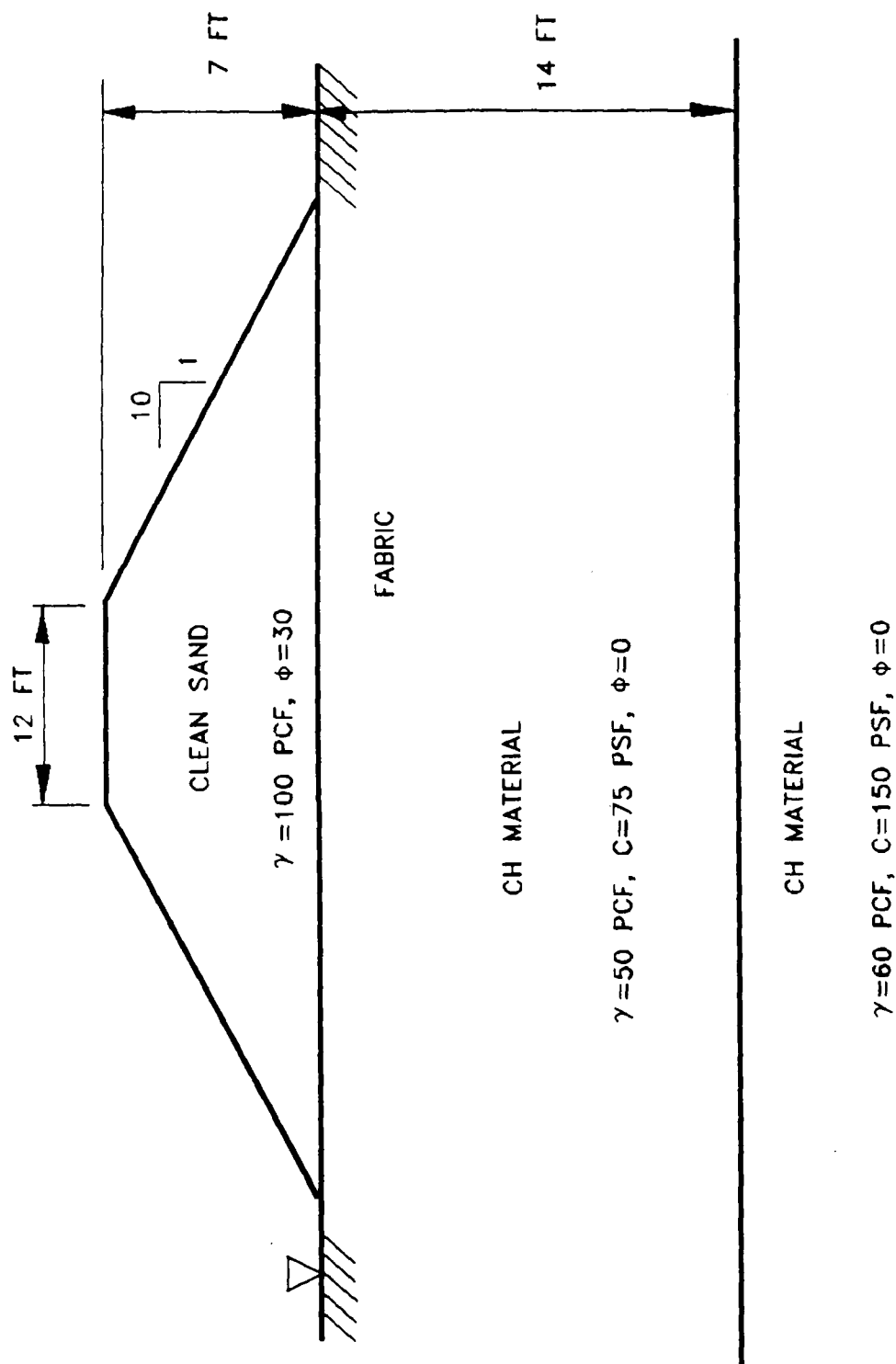


Figure 15. Embankment section and foundation conditions of embankment design example problem.

b. Applied Stress.

$$\sigma_v = \gamma_m H = 100(7) = 700 \text{ psf}$$

- c. Determine factor of safety. It is obvious that the bearing capacity is not sufficient for an unreinforced embankment, but for a geotextile-reinforced embankment, the lower portion of its base will act like a mat foundation, thus distributing the load uniformly over the entire embankment width. Then, the average vertical applied stress is:

$$q_a = [2(\sigma_v \times L/2) + \text{Crest width} \times \phi_v] / (2 \times \text{Dike slope width} + \text{Crest width})$$

$$q_a = [2(700/2 \text{ psf} \times 70 \text{ ft}) + 12 \text{ ft} (700 \text{ psf})] / (2 \times 70 \text{ ft} + 12 \text{ ft})$$

$$q_a = 378 \text{ psf}$$

$$F_s = q_{ult}/q_a = 378 \text{ psf}/385 \text{ psf} < 1.0$$

If a dried crust is available on the soft foundation surface, then the factor of safety is about 1.0. If no surface crust is available, the factor of safety is less than 1.0, and the embankment slopes or the crest height would have to be modified. Since the embankment is very wide and the soft clay layer is located at a shallow depth, failure is not likely because the bearing capacity analysis assumes a uniform soil strength twice the depth of the embankment width.

Bearing Capacity Consideration

58. A second bearing capacity consideration is the chance of soft foundation material squeezing out. Therefore, the lateral stress and corresponding shear forces below the embankment, with respect to resisting passive forces and shear strength of soil, are determined.

- a. Plastic flow. Plastic flow method for overall squeeze-squeeze between two plates.

$$c_{\text{required}} = (\sigma_v \times a)/L \quad (\text{Eq 14})$$

where

c = cohesion (shear strength) of soil

a = 1/2 distance between embankment and next higher strength foundation soil layer

L = width of embankment

For the example as discussed earlier.

$$C_{\text{required}} = (700 \text{ psf})(14 \text{ ft}/2)/(140 \text{ ft} + 12 \text{ ft})$$

$$C_{\text{required}} = 32.2 \text{ psf}$$

Cohesion available is 75 psf, greater than 32.2 psf required.

b. Passive resistance for toe squeeze.

$$P_a \text{ (just below embankment)} = \gamma_m H - 2c + \sigma_v \quad (\text{Eq 15})$$

$$P_p \text{ (resisting squeeze)} = \gamma_m H + 2c \quad (\text{Eq 16})$$

Then the difference is:

$$P_p - P_a = \gamma_m H + 2c - (\gamma_m H - 2c + \sigma_v) \quad (\text{Eq 17})$$

$$P_p - P_a = 4c - \sigma_v \quad (\text{Eq 18})$$

For the example:

$$P_p - P_a = 4(75) - 378$$

$$P_p - P_a = 300 - 378$$

$$P_a - P_p = 78 \text{ psf}$$

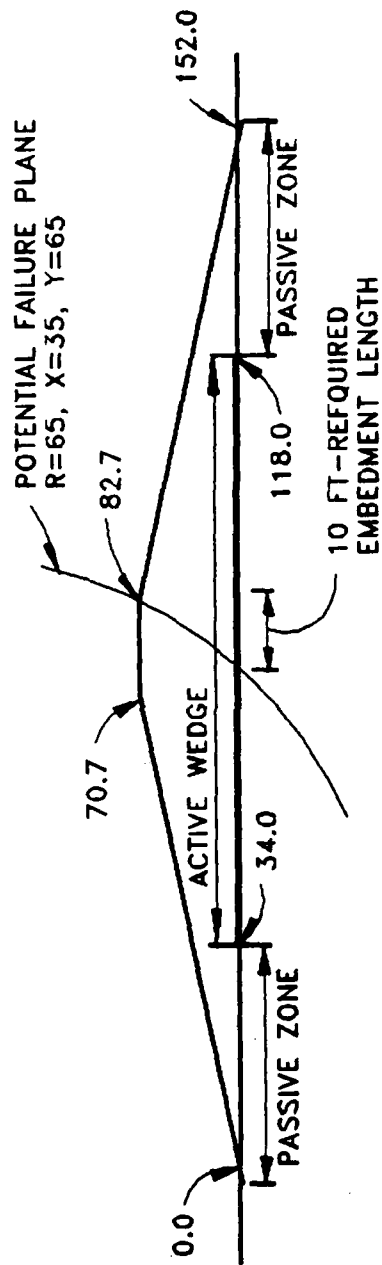
P_a is greater than P_p ; therefore, foundation squeeze may occur. Solutions would be to either allow squeezing to occur or construct shallow berms to stabilize the embankment toe or use plastic strip drains.

c. Slope stability analysis. A slope stability analysis performed to determine the required fabric tensile strength and modulus to provide a factor of safety of 1.3 against rotational slope failure. There are many slope stability procedures available in the literature for determining the fabric tensile strength

T . The slope stability analysis used for this example was performed using the two-dimensional slope stability package UTEXAS2, version 1.209 (Instructional Report GL 87-1). Of the four limit equilibrium analysis procedures available in this program, Spencer's procedure was used for all analyses. This method satisfies both force and moment equilibrium by assuming that the side force inclination is constant. The user is referred to the UTEXAS2 User's Guide, Vol. I, 1987, for the theoretical details of the various analysis procedures.

- (1) For the example, the phreatic surface is assumed to be at the top of the clay layer. The origin of the coordinate system is assumed to be at the left dike toe. Circular shear surfaces were used for all of the searches to determine the critical shear surface.
- (2) The shear surface contains an active and passive zone, but the geotextile can only carry tension in the active zone. The first step in the analysis is to determine the critical circle without geotextile reinforcement. The x value of the critical circle for this search is the boundary between the active and passive zone. For this example, the critical circle without reinforcement has a safety factor of 0.98 with an x center value of 34 ft.
- (3) The next step is to add the reinforcement to the analysis. With the program UTEXAS2, the reinforcement is specified as straight line segments with a given tension. For this example, the reinforcement is specified as illustrated in Figure 16. With the geotextile tension added, a circular search is performed, with the center values from the previous search as the starting point. The tension in the reinforcement is varied until the safety factor for the critical shear surface is 1.3. For this example, a reinforcement tension, T of 2,800 lb/ft width or 233 lb/in. width is necessary to increase the safety factor to 1.3.
- (4) Pullout resistance of the fabric from the intersection of the potential failure plane surface is determined by calculating the resistance and necessary fabric embedment length. Intersection of this failure plane was determined to be at coordinates 76, 0. There are two components to fabric pullout resistance - one below and one above the fabric. Resistance below the fabric in this example is 50 psf, and resistance above the fabric is determined by the average height of fill above the fabric in the affected areas. In this example, the resistance above and below the fabric is determined as follows:

$$R = \gamma_m h \tan \phi_1 + C_r \quad (\text{Eq 19})$$



EL -14

INPUT DATA (UTEXAS2, VERSION 1.209)

REINF.

1	1				
0	0	0	0		
34	0	0	0		
34.1	0	0	2800	} FABRIC TENSION VALUE IN POUNDS PER FT-WIDTH	
117.9	0	0	2800		
118	0	0	0		
152	0	0	0		

Figure 16. Reinforcement representation for UTEXAS2.

where

γ_m = moist weight of sand fill, 100 pcf

h = average height of sand fill above fabric in the affected area, 6.5 ft

ϕ_1 = sand-fabric friction equal to $(2/3)\phi$

C_r = remolded strength of foundation clay soil beneath the fabric, 50 psf

$$R = (100)(6.5 \text{ ft}) \tan [(2/3) 30^\circ] + 50 \text{ psf}$$

$$R = 287 \text{ psf-width}$$

The required pullout length is determined from ultimate tensile strength requirement determined from UTEXAS2, where $T = 2,800 \text{ lb/ft-width}$ or 233 lb/in. width . Therefore,

$$L = T/R = 2,800 \text{ lb/ft-width} / 287 \text{ lb/ft}^2\text{-width}$$

$$L = 9.8 \text{ ft; approximately } 10 \text{ ft}$$

d. Factor of safety. Calculate ϕ_{sf} to provide a factor of safety of 2.0 against sliding failure across the geotextile.

(1) Calculate lateral earth pressure, P_A ;

$$P_A = (0.5) \gamma_m H^2 \tan^2 (45^\circ - \phi/2)$$

$$P_A = 0.5 (100 \text{ pcf}) (7 \text{ ft})^2 \tan^2 (45^\circ - 30^\circ/2)$$

$$P_A = 817 \text{ lb/ft-width}$$

(2) Calculate ϕ_{sf} :

F_s = Resisting Force, P_R /Driving Force, P_A

$$F_s = [0.5 \gamma_m X H^2 \tan \phi_{sf}] / [0.5 \gamma_m H^2 \tan^2 (45^\circ - \phi/2)]$$

$$\tan \phi_{sf} = (F_s/X) \tan^2 (45^\circ - \phi/2)$$

$$\tan \phi_{sf} = (2.0/10) \tan^2 (45^\circ - 30^\circ/2)$$

$$\tan \phi_{sf} = (0.2)(\tan^2 30^\circ) = (0.2)(0.58)^2$$

$$\phi_{sf} = \tan^{-1} (0.07)$$

$$\phi_{sf} = 3.9^\circ$$

- e. Geotextile tensile strength. Calculate required geotextile tensile strength (T_F) to provide an FS of 1.5 against splitting.

FS = 1.5 against splitting

P_A = 817 lb/ft-width

Calculate T_F :

$$T_F = 1.5 P_A$$

$$T_F = (1.5)(817 \text{ lb/ft-width})$$

$$T_F = 1,226 \text{ lb/ft or}$$

$$T_F = 102 \text{ lb/in.-width}$$

- f. Tensile modulus. Calculate the tensile modulus E_F required to limit embankment average spreading and rotation to 5 percent fabric elongation.

(1) Spreading analysis:

$$E_F = 20 T_F$$

$$E_F = (20)(102 \text{ lb/in.-width})$$

$$E_F = 2,040 \text{ lb/in.-width}$$

(2) Rotational slope stability analysis:

$$E_{FR} = 20 T$$

$$E_{FR} = (20)(T = 233 \text{ lb/in.-width})$$

$$E_{FR} = 4,670 \text{ lb/in.-width}$$

- g. Tensile strength requirements. Determine geotextile tensile strength requirements in fabric fill (weft) and across seams. Tensile strength requirement in this direction depends on the amount of squeezing out and dragging loads on the under side of the fabric and the amount of shoving or sliding that the 2 to 3 ft of sand fill material causes during initial placement. If three panels 16-ft wide are in place and the foundation material moves longitudinally along the embankment alignment because of construction activities when establishing a working platform (Figure 14), then the loads in the fabric fill direction can be calculated as follows:

- (1) Fabric fill and seam tensile strength requirement:

$$T_{FRF} = (3 \text{ panels})(16\text{-ft wide}) C_r$$

C_r = remolded shear strength of foundation materials

$$T_{FRF} = (3)(16 \text{ ft})(50 \text{ psf})$$

$$T_{FRF} = 2,400 \text{ lb/ft-width}$$

$$T_{FRF} = 200 \text{ lb/in.-width}$$

$$T_{FRF} \text{ at FS of 1.5} = 300 \text{ lb/in.-width}$$

- (2) Fabric fill and seam tensile modulus of 10 percent elongation:

$$E_{FRF} = 10 T_{FRF}$$

$$E_{FRF} = 3,000 \text{ lb/in.-width}$$

- h. To summarize minimum fabric specification requirements. If the fabric chosen is a woven polyester yarn and only 50 percent of the ultimate fabric load is used, then the minimum ultimate strength is 2.0 times the required working tensile strength 233, or 467 lb/in.-width to compensate for possible creep.

- (1) Soil-fabric friction angle, $\phi_{SF} = 3.9 \text{ deg.}$
- (2) Ultimate tensile strength T_{ULT} in the fabric warp directions working tensile strength = 467 lb/in.-width.
- (3) Ultimate tensile strength T_{FRF} in the fabric fill and cross seams directions = 300 lb/in.-width.
- (4) Secant tensile modulus at 5 percent fabric elongation in fabric warp direction is 4,670 lb/in.-width, (based on working tensile strength) and 10 percent fabric elongation in the fill and cross seam directions is 3,000 lb/in.-width.
- (5) AOS less than or equal to 30 sieve size.
- (6) Contractor survivability and constructability requirements are included in Tables 2, 3, and 4. Fabric specifications must meet or exceed these requirements.

Fabric-Reinforced Embankment Construction

59. Proper specification of construction procedures for building fabric-reinforced embankments on soft foundation material must be emphasized, as desired fabric behavior cannot be obtained without specific sequential construction procedures. If construction is let to an inexperienced contractor, conventional no-fabric construction procedures may be chosen since these will (seemingly) be the fastest and, thus, more cost-effective. Conventional procedures usually consist of placing fill material along the embankment centerline and spreading it toward the toes. If such procedures are followed, adequate fabric anchorage cannot be developed, and the attempt to build the embankment to the height prescribed by design will usually result in project failure. The proper backfill placement procedure to pretension the fabric for moderate and soft foundation condition is shown in Figure 17.

Equipment Selection

60. Successful construction of embankments on soft foundation material is very dependent upon the selection of low ground pressure construction equipment, which will not produce remolding or induce bearing failure of the foundation material. Small wide-track dozers (30-in. wide), with maximum 2.5 to 3.0 psi ground pressure are required for spreading fill material on the fabric. Properly designed and constructed fabric-reinforced haul roads on soft soil will carry loaded 12 to 15 cu yd tandem-axle dump trucks.

- a. Site-specific conditions. Site-specific conditions may allow the use of either higher or lower ground pressure equipment and may permit the use of partially loaded dump trucks during initial placement of fill material, to prevent foundation bearing failure.
- b. Additional equipment requirements. Additional construction equipment requirements include the use of a portable field sewing machine to sew fabric field seams. Thread used should be of sufficient strength to provide a sewn seam strength equal to or greater than the strength of the engineering fabric, in both machine (warp) and cross-machine (fill) directions. High-strength polypropylene, polyester, nylon, or Kevlar thread are recommended for sewing high tensile strength engineering fabrics. If the field sewing machine does not make locked stitches to prevent unraveling, then each seam should be at least double-sewn. The thread should be tied off at the end of

Table 2

Required Degree of Fabric Survivability (see Table 4) As a Function
Of Subgrade Conditions and Construction Equipment (FHWA 1984)

Subgrade Conditions	Construction Equipment and 6 to 12 inch Cover Material Initial Lift Thickness		
	Low Ground Pressure Equipment ≤4 psi	Medium Ground Pressure Equipment >4 psi, ≤8 psi	High Ground Pressure Equipment >8 psi
Subgrade has been cleared of all obstacles except grass, weeds, leaves, and fine wood debris. Surface is smooth and level such that any shallow depressions and humps do not exceed 6 inches in depth and height. Alternatively, a smooth working table may be placed.	Low	Moderate	High
Subgrade has been cleared of obstacles larger than small- to moderate-sized tree limbs and rocks. Tree trunks and stumps should be removed or covered with a partial working table. Depressions and humps should not exceed 18 inches in depth and height. Larger depressions should be filled.	Moderate	High	Very High
Minimal site preparation is required. Trees may be felled, delimbed, and left in place. Stumps should be cut to project not more than 6 inches above subgrade. Fabric may be draped directly over the tree trunks, stumps, large depressions and humps, holes, stream channels, and large boulders. Items should be removed only if placing the fabric and cover material over them will distort the finished road surface.	High	Very High	Not recommended

NOTES:

1. Recommendations are for 6 to 12 inch initial thicknesses. For other initial lift thickness:
 12 to 18 inch: Reduce survivability requirement 1 level
 18 to 24 inch: Reduce survivability requirement 2 levels
 >24 inch: Reduce survivability requirement 3 levels
2. Survivability levels are, in increasing order: low, moderate, high, and very high. For special construction techniques such as pre-rutting, increase fabric survivability requirement 1 level.
3. Placement of excessive initial cover material thickness may cause bearing failure of soft subgrades.

Table 3
Required Degree of Fabric Survivability as a Function of
Cover Material and Construction Equipment (FHWA 1984)

<u>Required Degree of Fabric Survivability</u>	<u>Grab Strength (minimum values)¹ lb</u>	<u>Puncture Strength² lb</u>	<u>Burst Strength³ psi</u>	<u>Trap Tear⁴ lb</u>
Very High	270	110	430	75
High	180	75	290	50
Moderate	130	40	210	40
Low	90	30	145	30

1. All values represent minimum average roll values (i.e., any roll in a lot should meet or exceed the minimum values in this table). Note: These values are normally 20 percent lower than manufacturers reported typical values.
2. ASTM D 571-68, Tension Testing Machine with ring clamp, steel ball replaced with a 5/16-inch diameter solid steel cylinder with flat tip centered within the ring clamp.
3. ASTM D 751-68, Diaphragm Test Method.
4. ASTM D 1117, either principal direction.

Table 4

AASHTO-AGC-ARTBA Joint Committee (Interim Specifications)

Minimum Fabric Properties Required for Fabric

Survivability (FHWA 1984)

Cover Material	6 to 12 inch		12 to 18 inch		18 to 24 inch		>24 inch	
	Initial Lift Thickness Low	Initial Lift Thickness Medium	Initial Lift Thickness Medium	Initial Lift Thickness High	Initial Lift Thickness High	Initial Lift Thickness High	Initial Lift Thickness High	Initial Lift Thickness High
Fine sand to ± 2 -in.-diam gravel, rounded to subangular	Ground Pressure Equipment ≤ 4 psi	Ground Pressure Equipment > 4 psi, ≤ 8 psi	Ground Pressure Equipment > 4 psi, ≤ 8 psi	Ground Pressure Equipment > 8 psi	Ground Pressure Equipment > 8 psi	Ground Pressure Equipment > 8 psi	Ground Pressure Equipment > 8 psi	Ground Pressure Equipment > 8 psi
	Moderate	High	Moderate	High	Moderate	High	Moderate	High
	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate
Coarse aggregate with diameter up to one-half proposed lift thickness, may be angular	Moderate	High	Moderate	High	Moderate	High	Moderate	High
Some to most aggregate with diameter greater than one-half proposed lift thickness, angular and sharp-edge few fines	High	Very High	High	Very High	High	Very High	High	Moderate

NOTES:

- For special construction techniques such as pre-rutting, increase fabric survivability requirement 1 level.
- Placement of excessive initial cover material thickness may cause bearing failure of soft subgrades.

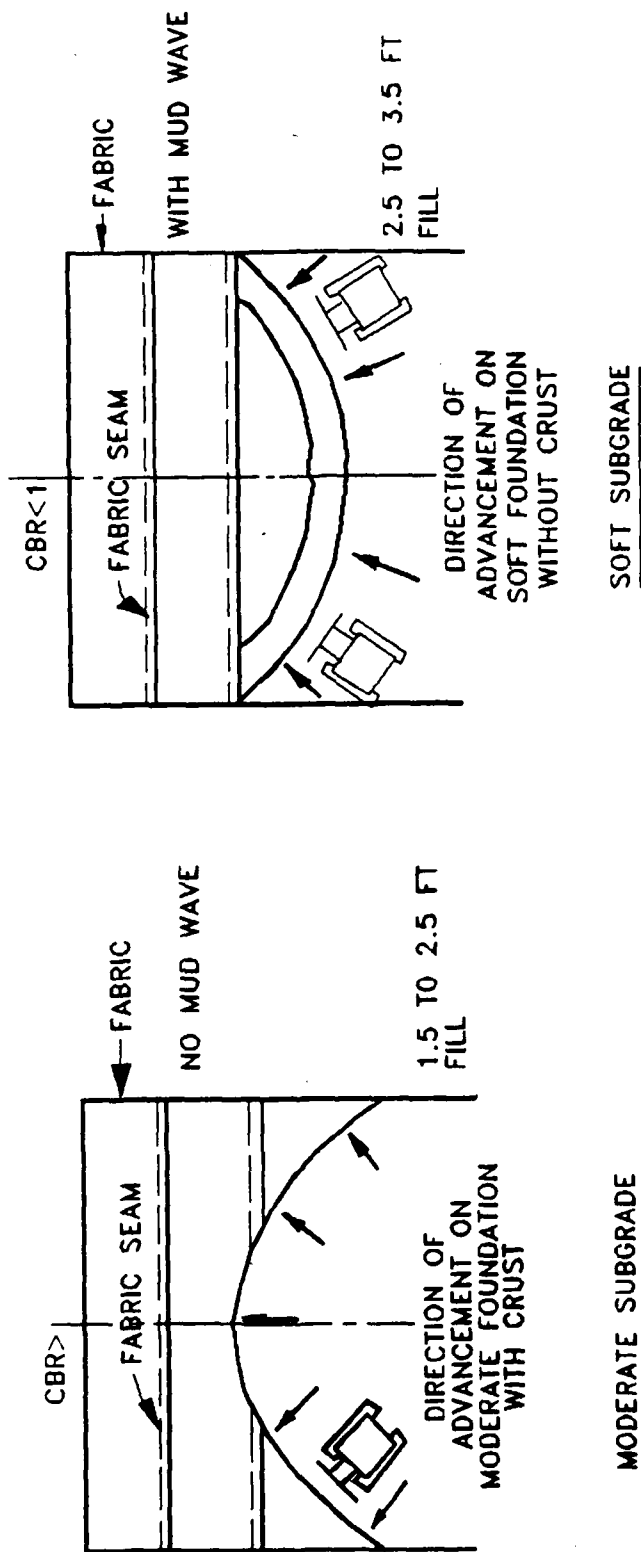


Figure 17. Placement of first lift to pretension fabrics on moderate and soft ground conditions.

each sewing pass and at other locations where thread ends are produced to prevent in-service unraveling. A portable generator may be required to provide power for the field sewing machine.

Site Preparation

61. Site preparation prior to fabric placement will depend on existing conditions along the alignment including foundation strength and its relation to equipment mobility, presence of a vegetative root mat, need for removal of large trees or other obstructions, and other factors necessary to provide a working surface compatible with the survivability and workability requirements of the selected engineering fabric. As a practical matter, use of high survivability fabric will speed the rate of embankment construction. Experience indicates that construction of working tables for fabric placement is not cost effective when compared with direct placement of high-survivability fabric. However, construction of a working table will facilitate fabric placement and sewing operations and will improve soil-fabric friction capabilities on the under side of the geotextile.

- a. Requirements for fabric survivability properties. Table 2 may be used to determine required fabric survivability properties for given foundation conditions or, conversely, to determine site preparation requirements for placement of a given fabric. Engineering fabric field workability property requirements may be taken from Table 3, based on foundation strength. Where soft foundation conditions exist, it is advisable to leave a small vegetative cover, such as grass and weeds, in place to provide a matting to support contractor personnel. Table 4 may be used to determine the minimum fabric properties required for fabric survivability.
- b. Fill. Any large depressions, ditches, shallow creek channels, and other similar features found along the embankment alignment, where a reasonable amount of fill will be necessary to obtain design grade, should have fabric unrolled along the alignment (over the existing surface depression) with fill placed on this fabric to the approximate adjacent ground elevation. This fill can later be covered by the fabric layer used for embankment reinforcement. The underlying fabric layer should be taken back some 6 to 8 ft along existing grade elevations on either side of the depression to provide future anchorage development.

- c. Need for working table. There will not usually be a need for construction of a working table prior to fabric placement because:
- (1) Engineering fabric may be chosen with high survivability to resist puncture or tearing during placement and embankment construction, thereby eliminating need for extensive site preparation to protect the fabric.
 - (2) Engineering fabric with needed workability may be selected to provide a stable working surface.
 - (3) For embankment construction on very soft foundation material, construction procedures will propagate a mud wave which will destroy any working table. In this instance, the working table is the mud wave. Selection of engineering fabrics with good field workability and survivability properties can greatly reduce site-preparation requirements but should be justified with a benefit-cost analysis, as will be discussed later.

Fabric Placement Procedures

62. Engineering fabric placement is a hand-labor-intensive procedure which may be simplified by prefabricating fabric panels before field placement. Factory prefabrication procedures are presented:

- a. Loom width. Manufacture fabric to the largest loom width possible.
- b. Maximum cross-machine direction-width. Sew fabric strips together to provide the maximum cross-machine direction-width compatible with shipping and with field handling requirements.
- c. Shipping. Ship fabric rolls in unseamed machine-direction lengths equal to one or more multiples of the embankment design width.
- d. Presewing. Presew factory fabric with high-strength polypropylene, polyester, nylon, or Kevlar, or combinations of these threads, to give a seam strength at least equal to the cross machine direction, wide-width tensile strength. Two-thread chain-locked stitching should be used.
- e. Following construction-site delivery. Unroll and field-sew the fabric to the maximum width which can be handled by construction personnel and place along the embankment alignment. Additional fabric panels may be fabricated away from construction activities while fill material is being placed, thereby reducing the construction equipment idle time. Fabric should always be sewn, rather than overlapped, or slippage may occur between fabric strips, exposing embankment materials, and risking embankment instability.

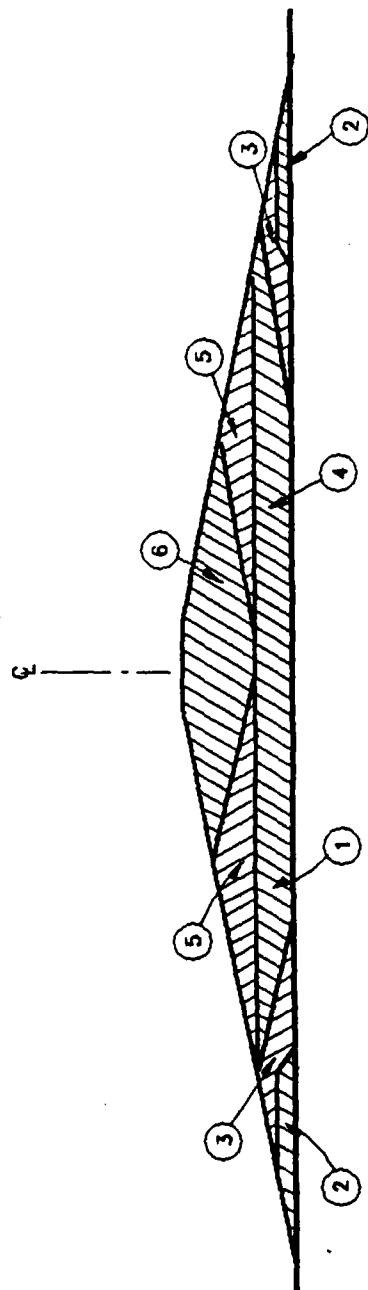
Fill Placement/Spreading/Compaction Procedures

63. Following fabric placement, embankment fill may be placed by end-dumping. While small (5 cu yd) dump trucks are desirable for initial fill material placement because of their lower weight, larger tandem-axle trucks in the 10 to 15 cu yd range may be used if these are the only vehicles available. However, in such instances, the actual volume of fill material carried by the truck may have to be reduced to eliminate the possibility of foundation bearing failure and subsequent damage to the engineering fabric. A minimum of 18 in. of fill material should be maintained at all times between the tires of the dump trucks and the fabric. After more than 18 in. of fill material has been placed on the fabric, dump trucks may be loaded heavier and, after 2 to 4 ft of material has been placed to cover the fabric, the dump trucks may be loaded to total capacity. If fill material is placed by back-dumping, trucks should be prevented from backing onto and damaging the engineering fabric.

- a. Spreading and compaction. After material is placed on the fabric, final spreading and compaction may be carried out by small dozer equipment and/or front-end loaders. A minimum cover of 6 to 12 in. should be maintained between construction equipment and fabric, with thickness depending upon degree of site preparation performed prior to fabric placement and upon fabric survivability properties.
- b. Pneumatic rolling. If additional fill compaction is desired after spreading, grading, and track/tire compaction, pneumatic rolling is recommended. Sheepsfoot rollers should not be used for initial compaction as feet may puncture the fabric and, in any case, they are not suitable for compaction of granular material. Vibratory rolling equipment is not recommended as its use may cause development of localized "quick" conditions.

Construction Sequence for Fill Material Placement

64. As stated previously, validity of the recommended design concepts depends upon a sequential construction procedure to mobilize fabric support. If the construction sequence is not followed, embankment instability may occur. Figure 18 illustrates the proper construction sequence.



SEQUENCE OF CONSTRUCTION

- ① LAY FABRIC IN CONTINUOUS TRANSVERSE STRIPS, SEW STRIPS TOGETHER.
- ② END DUMP ACCESS ROADS.
- ③ CONSTRUCT OUTSIDE SECTIONS TO ANCHOR FABRIC.
- ④ CONSTRUCT INTERIOR SECTION TO "SET" FABRIC.
- ⑤ CONSTRUCT INTERMEDIATE SECTIONS TO TENSION FABRIC.
- ⑥ CONSTRUCT FINAL CENTER SECTION.

Figure 18. Recommended construction sequence for fabric-reinforced embankments.

- a. Laying fabric and initial fill material placement. Step 1 consists of laying fabric in continuous transverse strips and performing any necessary sewing, as discussed under fabric placement procedures. Initial fill material placement, during step 2 operations, creates haul/access roads along the embankment edges, and more importantly, the fill material serves to anchor the fabric so that its tensile stresses may be developed during subsequent construction phases.
- b. Added fabric layer. After 6 to 12 in. of fill material has been placed over the reinforcing fabric layer placed during step 2, a second fabric layer may be unrolled along each embankment toe with the machine (warp) direction parallel to the embankment alignment, and 6 to 12 in. additional fill placed over this second fabric layer. This added fabric layer will serve, in conjunction with the initial reinforcement fabric, as reinforcement in a double-fabric-layer haul/access road capable of sustaining heavier traffic loading and 10 to 15 cu yd tandem-axle dump trucks may be loaded to capacity, thus speeding fill material placement during steps 3 through 6.
- c. Fill material for anchoring. After edge access/haul roads are constructed, fill material is placed in location 3 to complete the anchoring process. Embankment fill material is next placed at location 4 to set the fabric, and dump trucks may then begin end-dumping fill material at embankment quarter points, as indicated in step 5, to tension the engineering fabric. The trucks use the two haul roads for entering/exiting the embankment alignment and are diverted to the center only to reach a designated dump point.
- d. Completion of construction. Finally, embankment fill material is placed in the center section as indicated by step 6; the embankment is shaped, and construction is complete.
- e. Mud wave formation. As construction progresses using this sequence, mud wave formation may occur below the fill material in a manner similar to that depicted in Figure 14. The outer edges of embankment fill placement (steps 1-3) should be kept 50 to 100 ft ahead of step 4 fill placement to develop a "U" configuration at the working face (Figure 17). By use of this construction sequence, the mud wave will be contained between the outer embankment edges, thus mud wave movement will be forward along the embankment alignment. If men cannot walk ahead of the "leading edge" fabric strip because of soft foundation conditions, a new strip may be sewn to the upturned edge of the "leading" strip, and then "thrown" out or launched with long wooden poles onto the mud wave. Placement of additional fill will shove the mud wave forward and stretch the fabric. A new fabric strip should then be attached in similar manner. Fabric with very high field workability is required.

- f. Fabric placement. Fabric placement is facilitated by working on the mud wave. However, fabric layers should not be placed far ahead of the mud wave, or else the fabric may be overstressed by friction between the mud wave and the fabric, such that mud wave forward progress will create tensile forces exceeding fabric/seam cross-machine tensile strength. Procedures to eliminate such problems will result in U-shaped construction with the central embankment section progressing at the same rate as the leading embankment edges, with only one or two fabric strips placed ahead of the fill covering operation.

Discussion of Construction Procedures

65. Although the construction procedures outlined in this section are not complicated, they must be followed to assure proper performance. The fill placement sequence is extremely important and opposite from that used in conventional non-fabric construction. Additionally, care must be taken to ensure that construction proceeds along each embankment edge concurrently and that balanced fill placement procedures are used. On soft cohesive foundations, rapid fill placement will create a "zero effective stress" condition in the foundation such that classic "floating" conditions are developed, and, if unbalanced forces are generated by non-symmetrical fill placement, the floating embankment will "tip over" or slide laterally. Problems may also occur from lateral sliding of the intact embankment if a large ditch or channel is adjacent to the alignment. In such instances, lateral sliding stability of the embankment should be checked by conventional slope stability procedures.

Benefit-Cost Ratio Determination

66. A proper benefit-cost ratio analysis must be performed to justify fabric-reinforced embankment construction versus conventional design and construction procedures. It should consider variations in fabric field workability and/or survivability. In general, engineering fabrics required for reinforcement will have good survivability properties, but workability properties are independent of fabric strength. Cost differences between fabrics with poor and good field workability may or may not be sufficient to justify using a fabric with lower workability; therefore, this consideration should be evaluated in the analysis.

PART VI: CONCLUSIONS AND RECOMMENDED DESIGN AND
CONSTRUCTION CONSIDERATIONS

67. It is concluded that the design concepts and construction methodology presented in this paper is the state of the art for fabric-reinforced embankments constructed on soft foundation materials. Data collected from several case histories of fabric-reinforced embankments constructed on soft foundations has verified the design and construction techniques that have been developed for this soft foundation construction technique. Collection and evaluation of data from these case histories have verified the technical feasibility of the concepts and the applicability of these concepts for the continued and successful construction of several major fabric-reinforced embankment throughout the world.

Important Design Considerations and Recommendations

68. A summary of design and construction considerations and recommendations were evaluated as to their importance or lack of importance in fabric-reinforced embankments constructed on soft foundations and are listed below.

- a. Three potential modes of failure that should be considered prior to construction are bearing capacity, lateral sliding, and rotational or wedge failure. Pullout resistance or fabric anchorage should also be considered but is felt not to be important in very flat slope embankments of one to 10 horizontal.
- b. Criteria for fabric selection should include high strength woven fabrics exhibiting high modulus and low elongation less than 5 percent at the working load. These fabrics should also exhibit low creep properties under sustained loads, high soil-fabric friction and pullout resistance, wet strength properties, resistance to chemical and biological elements found in the environment and ultraviolet resistance prior to and during installation.
- c. It is highly recommended that low creep fabrics be considered during design. Where polyethylene, polypropylene, and polyesters are used, only 25, 40, and 50 percent of the ultimate load, respectively, should be used for the design working load.
- d. A very thorough geotechnical exploration of the foundation conditions should be required to obtain the necessary field vane shear strengths and soil samples for laboratory testing. Unconsolidated undrained Q triaxial compression tests and vane

shear tests are recommended for the cohesive soil and direct shear tests for the cohesionless soils preferably in a relatively loose condition.

- e. Because of the considerable loss of strength from remolding of these very soft, high void ratio, and high moisture content foundation materials, it is recommended that remolded strength be determined during the field vane shear tests. Excessive construction activity causing foundation displacement will destroy 50 to 80 percent of the in situ shear strength of these cohesive materials.
- f. Cost for fabric-reinforced embankments is considered to be highly cost-effective when compared to a displacement embankment that may require 3 to 4 volumes of fill below the surface for one volume of fill above the surface.
- g. Pore water pressure should be monitored prior to additional incremental dike construction and an evaluation of the dike stability should be made based on the available undrained-unconsolidated shear strength and available fabric strength. The use of strip drains will result in a considerable amount of embankment subsidence caused by consolidation of the soft foundation soils but will also result in higher foundation shear strengths and a much more stable embankment.
- h. It is highly recommended that an embankment stability analysis be conducted prior to allowing any incremental embankment construction activity. It is also recommended that all construction activities be monitored and that the design requirements are not exceeded.
- i. Seam strength requirements for the fabric fill direction should be based on the amount of cohesion between the foundation soil and fabric when a mud wave is anticipated to squeeze out during construction of the working table.

Important Construction Considerations and Recommendations

- a. Fabric seams should always be oriented transverse to the longitudinal direction of the embankment and the amount of fabric subjected to squeezing out of the foundation materials used in the design should not be exceeded. Placement of too many fabric strips on the mud wave surface increases the tensile load across the fabric seams when the mud wave displaces as a result of the equipment and fill load causing a shallow bearing capacity and displacement failure.
- b. Factory and field seams should be constructed using high strength threads with two parallel rows of stitches preferably using the "J" seam.

- c. Sequential construction of fill material in a horseshoe shape on the fabric is a very effective method of controlling displacement of soil foundation material when the surface does not contain a crust.
- d. Use of low-ground pressure equipment such as wide-tracked dozers less than 2.5 psi and light loaded tandem wheeled dump trucks is a critical element in the success of construction on soft foundations.
- e. When placing a fabric on a surface without crust on the surface, the fabric must exhibit sufficient stiffness to support workers during sewing and placement.
- f. All fabric strips must be continuous from toe to toe of an embankment without seams in the longitudinal direction.
- g. A fabric sampling program to test seam strengths and warp and fill strengths should be implemented on all fabric-reinforced embankment projects.

General Recommendations

69. It is recommended as, performance results from other fabric-reinforced embankments instrumented with strain gages, settlement plates, and piezometers becomes available, that embankments should be designed and constructed to prevent potential lateral spreading and rotational failure. It is recommended that a factor of safety of 2.0 for lateral spreading and bearing capacity failure be used during design. To determine the fabric working strength for potential rotational slope stability it is recommended that a factor of safety of 1.3 be used. It is recommended that the minimum stress-strain modulus used for the fabric not exceed more than five percent elongation at the designed working load. When site conditions permit it is recommended when possible that the surface materials be allowed to dry out to expedite fabric placement but it is not necessary.

70. The tests described and the resulting data presented herein, unless otherwise noted, were obtained from research conducted under the sponsorship of the Mobile, New Orleans, Savannah, Vicksburg, Philadelphia, Norfolk, and Huntington Districts, and the New England Division of the US Army Corps of Engineers and by the US Army Engineer Waterways Experiment Station. Permission was granted by the Chief of Engineers to publish this information.

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